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Validation of Simulations of Eddy Current Methods with Measurements on Phantom Materials for Biomedical Engineering R&D

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Abstract. In this paper simulations of eddy current measurements are validated with comparison to real measurements on phantom materials. Accurate computer simulation with valid results is a valuable research tool for development of novel medical diagnostic methods. Eddy current methods can potentially provide affordable noninvasive diagnostics and treatment. Using gelatin-based materials with calibrated electrical conductivity allowed making tissue phantoms with realistic electrical properties. The electric conductivity of the phantom materials was adjusted by changing its composition and using van der Pauw method for conductivity validation. Then Comsol Multiphysics simulations (using finite element method) of electric impedance of a planar coil on the tissue model are compared to impedance measurements of the planar coil on real phantom material with the same properties. From the results, it was evident that the finite element method can be used for eddy currents in biomedical engineering R&D up to 12 MHz frequency.

Keywords: Bioimpedance; Eddy Current; Finite Element Method; Gelatin-Based Phantom; van der Pauw method

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1. Introduction

In several biomedical applications, it is necessary to determine eddy current distribution in biological tissues. A variety of methods can be used to model the eddy current distribution in conducting materials. In this paper, we employ FEM (the finite element method) simulation and compare it to eddy current real phantom measurements to investigate the eddy current distribution in biological tissue phantom materials with valid electrical properties for biomedical engineering applications.

Gelatin-based tissue phantom materials with defined electric conductivity were produced. Those phantoms would be used in development of medical diagnostic systems that use bioimpedance measurement with eddy currents to estimate the health state or pathologic condition in the patient [6]. Electrical conductivity of the material was measured and calculated by van der Pauw method at frequency range 100 Hz to 1 MHz. The result was used as material parameters for FEM simulation in COMSOL Multiphysics.

The impedance of the material, measured with eddy current sensors, and simulation results were compared and discussed in order to evaluate FEM simulation accuracy of the eddy current measurement in biomedical applications.

2. Methods of measurements

To compare impedance of phantom measured by eddy current and simulation results, a special measurement method was worked out. This method included: (1) preparing the tissue mimicking phantoms, (2) designing of PCB-s with planar coils for eddy current measurements and long electrodes for van der Pauw impedance measurements, (3) calculating conductivity of the material with van der Pauw method, and (4) impedance measurements with planar coil sensors.

2.1. Gelatin Phantom Preparation

Two different gelatin-based tissue phantoms with conductivities similar to blood and brain grey matter were developed. To produce biological tissue mimicking phantoms with realistic tissue properties, the respective electric conductivities were obtained from the internet database and used as guidelines in phantom development (see Table 1) [7].

Gelatin-based material was used as the tissue-mimicking material as it is self-supportive with a relatively simple manufacturing process. The composition and production process has been well reported in several previous researches [5, 6]. The mixture generally consist of distilled water, sodium chloride (NaCl), ethyl 4-hydroxybenzoate, formaldehyde solution and gelatin powder. Different electrical conductivities of phantoms were achieved by adjusting different amounts of sodium chloride. The phantom mixture was placed into Plexiglas enclosure with two double-sided printed circuit boards (PCB) for measurements and calibration of phantom.

Table 1. *Electrical conductivity of tissues [7].*

Tissue	*Electrical conductivity at 10 kHz, [S/m]*	*Electrical conductivity at 1 MHz, [S/m]*	*Electrical conductivity at 10 MHz, [S/m]*
Blood	0.70290	0.82211	1.09670
Brain grey matter	0.11487	0.16329	0.29172

2.2. Calibration of the Gelatin Phantom

Van der Pauw method was used to calibrate the conductivity of the produced phantom material. The required tissue phantom conductivity was achieved by several and continues adjusting of material mixture recipe in respect to van der Pauw conductivity measuring results.

To make the van der Pauw method compatible, some special requirements were followed in design of phantom shaping Plexiglas enclosure and conductivity measurement PCBs:

- Four thin electrode stripes, on two PCBs on either side, had direct contact to the gelatin sample cube. When viewed top down as 2D, the point-like electrodes are exactly in the corner of the sample.
- The thickness of the sample must be constant and homogeneous [3].

Research made by Kasl and Hoch [10] shows that when the contacts are located across the edges and the resistance of the electrodes are sufficiently low compared to the sample resistance, like in this research, van der Pauw method is reliable [10].

Van der Pauw technique is based on measuring the voltage and current ratio. The measurement and calculation methods have been well reported in previous research [6]. Measuring was carried out with Wayne Kerr 6500 impedance analyzer at frequency range from 100 Hz to 120 MHz, however the measurement result accuracy was limited on a frequencies higher than 1 MHz due to measuring ability of the used tool and methods. For this reason, the values of electrical conductivity only at frequency range from 100 Hz to 1 MHz were used in following simulation. After measuring the resistivity and conductivity of the sample can be calculated.

2.3. Planar Coil Sensor Design

To measure impedance of the sample with eddy currents, planar coils were designed on the same PCB-s (Fig.1). The PCBs were ordered from the factory and the diameter of planar coil had to be 20.2 mm and trace width had to be 0.2 mm according to the design. The microscope measuring showed that the real dimensions of coils were different from designed ones (summarized in Table 2).

Table 2. *Comparison of ordered and real coil dimensions*

Dimensions of coil	*Factory order*	*Average microscope measurement*
Thickness of copper layer, [mm]	0.099	0.035
Coil track width, [mm]	0.135	0.2
Spacing between coil tracks, [mm]	0.264	0.2
Coil inner diameter, [mm]	4.6	5.07
Coil outer diameter, [mm]	20.2	19.75

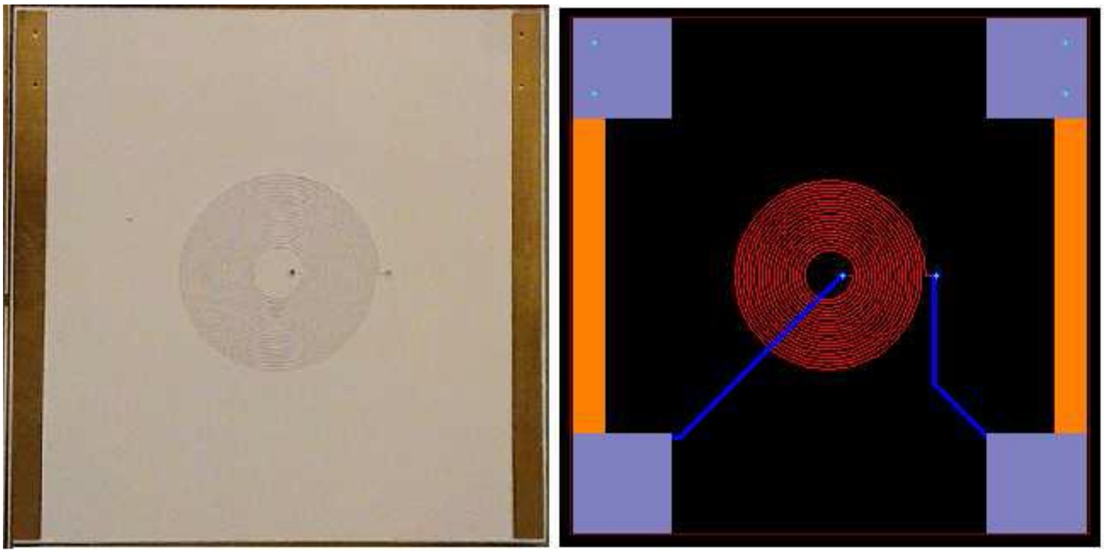

Figure 1. *PCB with planar coil in the middle and long strip electrodes on sides*

It was also specified that coil track consists of two different layers: (1) a pure copper layer, (2) and plated copper layer. The plated copper layer is much more resistive than pure copper [2].

2.4. Planar Coil Impedance Measurements

To measure impedance of the gelatin sample, PCBs were placed into the Plexiglas enclosure in a way that coils would be located on two opposite sides of the phantom and would have direct contact with it. Measurements were carried out with Wayne Kerr 6500 impedance analyzer at frequency range 100 Hz – 120 MHz. The induced voltage created by the eddy currents is proportional to the frequency and lags the primary excitation field by 90° [9].

3. Methods of Simulation

To simulate measurement results the model of gelatin phantom including planar coil sensor was designed using COMSOL Multiphysics 4.4 software. Material properties were specified and added to the necessary parts of the model geometry. Using the software, simulation was performed and results were visualized.

3.1. General Description of the Model

Simplified 2D axisymmetric model was created using the AC/DC Module for simulating electric, magnetic, and electromagnetic fields.

The AC/DC Module includes stationary and dynamic electric and magnetic fields. The AC/DC Module formulates and solves Maxwell's equations together with material properties and boundary conditions. The equations are solved using the FEM with numerically stable edge element discretization [1]. A multi-turn coil was designed and solved as RLC coil group in AC/DC Module.

3.2. Geometry of the Model

Model was created in 2D view and axial symmetry (shown on Fig. 2). The geometry dimensions are 100 mm x 100 mm and it consists of five main parts: (1) gelatin phantom, (2) air, (3) FR4 board, (4) layer of solder mask, and (5) multi-turn coil (summarized in Table 3, Fig.2).

As it was mentioned above, it was specified that coil track consists of plated copper layer and pure copper layer. Unfortunately, COMSOL was not able to solve the double-layered RLC coil group. For this reason, simplified single-layer coil track was designed. Coil tracks were coated by thin solder mask layer.

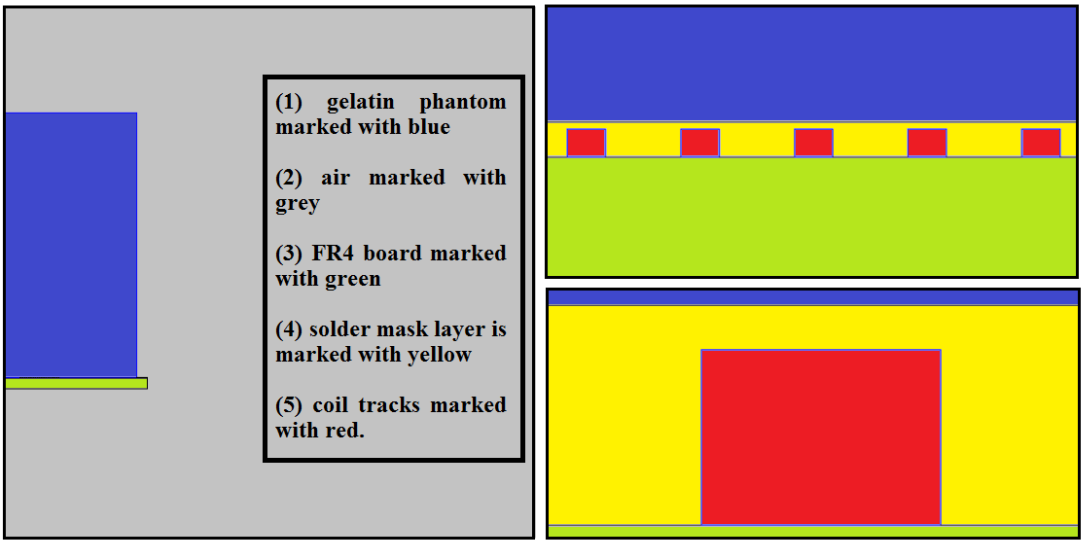

Figure 2. *Geometry of phantom model, zoomed in on right side.*

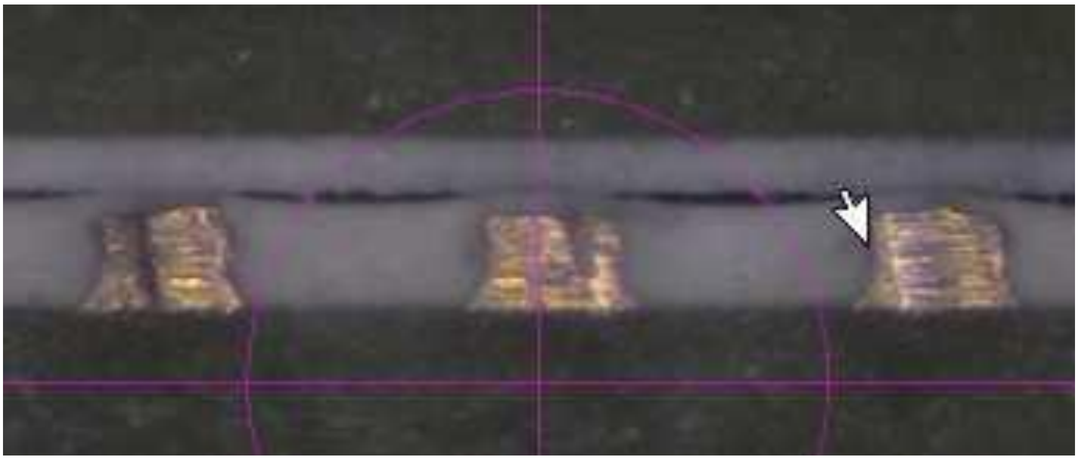

Figure 3. *Photo of PCB cut-through under measurement microscope.*

Table 3. *Geometry Dimensions*

Geometry part	*Width, [mm]*	*Height, [mm]*
Gelatin phantom	25	50
Air	100	100
FR4 board	27	2
Solder mask layer	27	0.025
Coil track	0.135	0.099

3.3. Material Properties of the Model

Materials and constitutive relations were defined in terms of permittivity, permeability and conductivity. Material properties were allowed to be spatially varying, time dependent, anisotropic, and have losses [1].

Electrical conductivity of the gelatin in the model was defined as results of van der Pauw method measurements and calculation for two different phantom materials: material A and material B.

Table 4. Electrical conductivity of materials in Comsol

Material	*Electrical conductivity, [S/m]*
Air [3]	1×10^{-6}
FR4 [3]	0.004
Solder mask [4]	1×10^{-5}
Pure copper [3]	5.88×10^{7}

3.3. Meshing and Solving the Model

Meshing of the geometry is dividing model into small elements. A free mesh consisting of triangular elements was created for the 2D geometry with COMSOL automatic mesh algorithm with three different mesh sizes. Mesh consisted of 326584 elements. Model was solved for the frequency range from 10 Hz to 120 MHz for two different materials.

4. Results

In this part, the results of simulation and planar coils measurements are presented. Fig. 4 shows the phase angle and impedance of material A at frequency range 100 Hz to 120 MHz. Later material B with different conductivity was simulated (Fig. 5). It was evident that measured impedance and the simulation values are good enough to facilitate simulation-research until 12 MHz. Phase angle differences are also manageable in the same frequency range.

It was also determined that planar coils are suitable for measuring homogeneous tissue mimicking materials in biomedical applications. Using planar coil on different phantom samples it is possible to see changes in impedance values depending on material conductivity (Fig. 6).

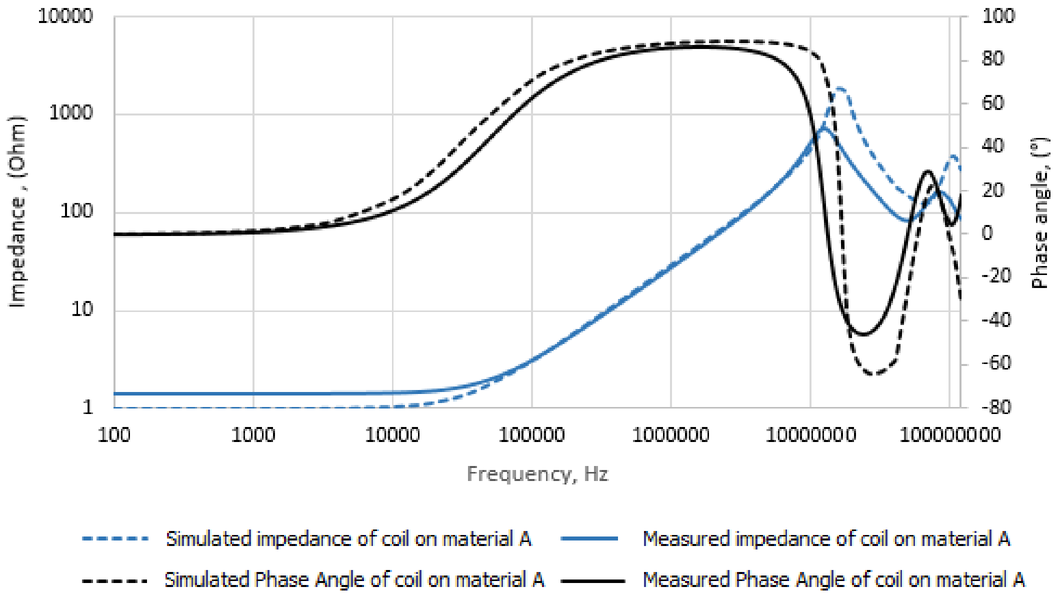

Figure 4. *Comparison of simulation and measurement results on material A.*

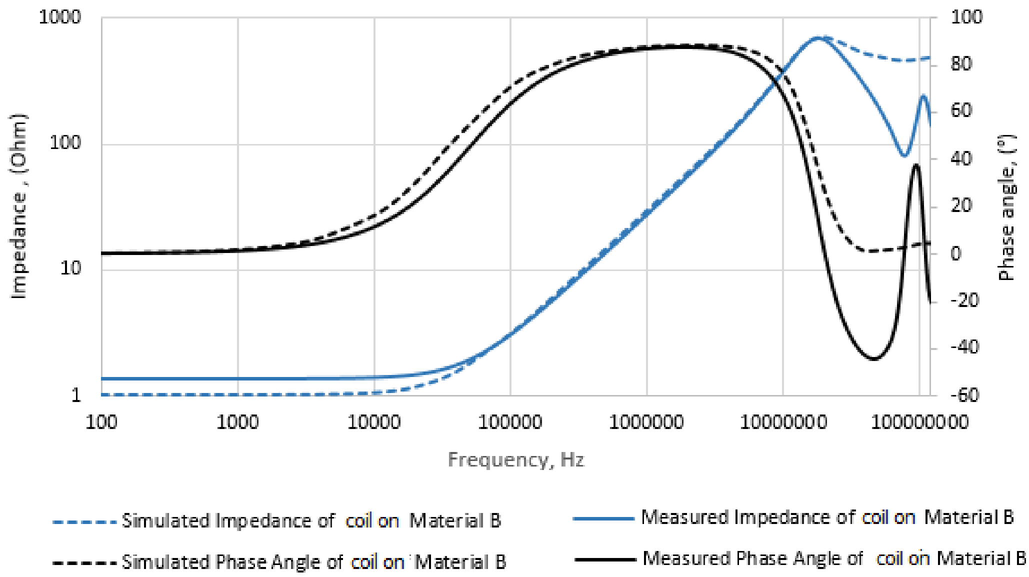

Figure 5. *Comparison of simulation and measurement results on material B.*

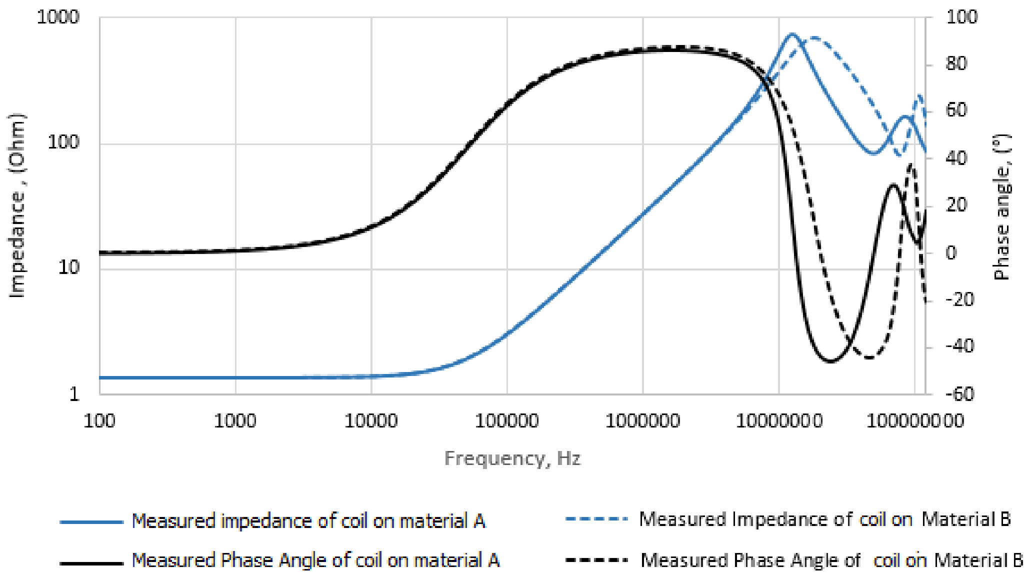

Figure 6. *Comparison of measurements results on materials A and B.*

5. Discussion

If as a result of the phantom material calibration experiments with van der Pauw method the composition of the material was mapped to the material properties. Electrical conductivity of investigated materials can be separately adjusted by changing of concentration of NaCl.

To evaluate the FEM simulation accuracy for developing of eddy current measurement method, a set of simulations was performed in COMSOL Multiphysics. From the results, it could be assumed that the FEM simulation method is reliable until 12 MHz frequencies. The difference in the simulated and measured signal was significantly higher at frequencies above 12 MHz. In addition, the resonance of signal appeared on different frequencies. Further research in this area is needed; however, the reasons of the resulting distortion could be suggested:

- Simplification of the COMSOL model geometry.
- Real material properties need to be investigated for every part of produced PCB.

• It was also specified that coil track consists of two layers with different electrical conductivity, but only one layer coil was modelled.

• Due to limited measuring ability of the used tool and methods, the electrical conductivity of phantom was measured and calculated only at limited frequency range (100 Hz to 1 MHz). However, the simulation was carried out also for higher frequencies.

In our future work we intend to focus on developing of eddy current sensors for biomedical engineering applications and to investigate more complex (inhomogeneous and multilayered) phantom samples with more realistic properties.

6. Conclusion

A planar coil with a diameter of 20 mm was positioned directly against the phantom material and was supplied with an AC current. Two different phantoms had conductivities similar to blood and brain gray matter, these were measured and calculated by van der Pauw method. COMSOL Multiphysics software was used to simulate the gelatin-based phantoms with calculated electrical conductivity. The results of simulation were compared to measurement with planar coil to evaluate FEM simulation accuracy for developing eddy current methods in biomedical applications.

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