Semi-analytical Modeling of Single Loop Inductive RF Sensors Used to Sense and Locate Inclusions in Dielectric Media

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Abstract— The electromagnetic characterization of dielectric media is a major issue in many industrial fields. Non-contact radiofrequency (RF) inductive techniques are well suited for the non-invasive evaluation and monitoring of dielectric media. In this paper, we investigated the relevance of a semi-analytical modeling technique, so-called distributed point source method (DPSM) to model the interactions of a RF single loop antenna with a dielectric medium containing a dielectric inclusion. The resistance of the antenna, which is related to the conductivity of the investigated media, can be estimated using DPSM. A series of experiments were carried out to validate the computed results. Furthermore, a simple system constituted of two RF single loop antennas is considered to locate the position of an inclusion. The DPSM was used to study the ability of such a system to locate the inclusion.

1. INTRODUCTION

The dielectric properties (electrical conductivity σ and dielectric permittivity ε) of organic media are recognized as relevant indicators of their physical state. The estimation of these properties is an interesting issue in many industrial fields, such as civil engineering, oil, food [1] or medicine [2]. Indeed, the dielectric spectroscopy techniques are widely used to characterize the state of the storage or processing of the food product [3] and the dielectric properties in the field of RF or in the field of microwave can be used as relevant indicators to detect and monitor the pathological evolution for human health and well-being [4–7]. However, because of contact issues [8], these techniques show limitations for *in-vivo*, for non-invasive or for wearable implementations. So the contactless inductive techniques have been developed for the dielectric characterization of organic media [7, 8]. Since the state of organic media affects both dielectric parameters [9], it seems relevant to consider RF techniques. To implement such a method, an RF antenna can be used as a transmit and receive sensor. The antenna radiates a variable magnetic field which induces eddy currents (related to the electrical conductivity) and displacement currents (related to the permittivity) of the medium. In turn, the induced currents change the radiated magnetic field by magnetic coupling. These changes may be sensed by reading out the RF antenna impedance changes. As a result, the analysis of the sensor impedance enables to read out the dielectric property changes of the medium. In this study, we aim at modeling the interactions between an RF antenna (a coil) and a dielectric medium (e.g., a tissue) containing a dielectric object of different properties (e.g., a lesion in a tissue). We investigate here the relevance of a semi analytical modeling, called the distributed point source method (DPSM), to accurately and efficiently model the interactions at stakes. In Section 2 of the paper, we present the studied configuration and the basic principle of the implementation of the DPSM. In Section 3, computations results are presented and validated by the experiment. In Section 4, a two coils configuration is studied so as to evaluate the possibility of localizing a dielectric inclusion within a dielectric medium.

2. IMPLEMENTATION OF DPSM MODELING

2.1. Studied RF Sensor Configuration

A simple sensor configuration was considered to evaluate the DPSM modeling. It is constituted of a single loop RF antenna interacting with a dielectric medium including a dielectric inclusion (see Fig. 1(a)). An experimental set up was built so as to validate the developed model (Fig. 1(b)). It is constituted of a PCB copper loop coil with a radius $R = 2\,\text{cm}$, which acts as a RF antenna. This antenna is placed above the surface of a tank full of a dielectric solution at a distance d_1 in the air, defined as medium 1, featured by σ_1 and ε_1. The loop is connected to a vector network analyzer (HP 4195A). The tank is filled with 10 liters of sodium chloride solution (medium 2, σ_2 and ε_2). A plastic ball with a radius $r = 4$ cm is used as an inclusion and filled with another solution (medium 3, σ_3 and ε_3). It is immerged below the interface medium1/medium2 with a distance d_2.

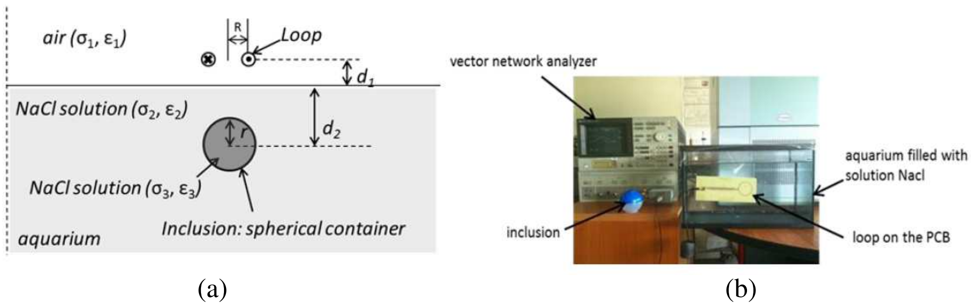


Figure 1: (a) Studied configuration. (b) General experimental instruments.

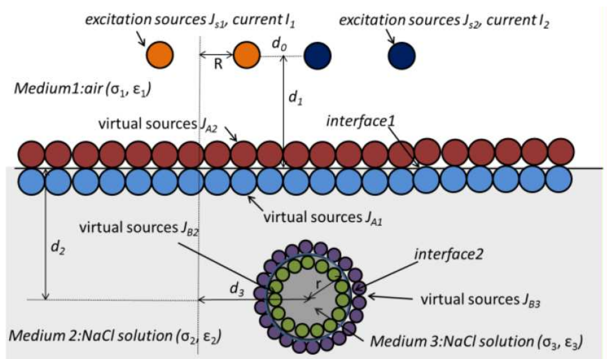


Figure 2: DPSM geometry meshing in case of an inclusion.

From [11], we know that the impedance of such a loop antenna varies with the dielectric properties of the medium with which it is electromagnetically coupled. More precisely, the real part of the loop impedance is associated to the losses within the media (conductivity σ) and the imaginary part of the impedance is linked to the permittivity ε. In our study, we focus on the sensing of the conductivity changes. the quantity of interest is therefore the variations of the real part of the loop impedance, ΔR:

$$\Delta R = \mathrm{Re}(Z_{load} - Z_0) \tag{1}$$

where Z_{load} is the antenna impedance coupled with the medium and Z_0 is the impedance in the air. The Re represents the mathematical operation 'real part'.

2.2. Basic Principles of the DPSM

The DPSM is a "mesh free" modeling technique, able to model 3D configurations with efficient computational implementations [10]. It basically consists in the radiation of the distributed point sources (DPS), which discretize the active radiation sources present in the workspace [10]. In our study, the active sources of RF antenna are modeled by a series of DPS which radiate as Green's functions. In addition to these actives sources, virtual DPS called interface sources are used to take account for the reflection/transmission effects between different media and boundary conditions. With the sum of radiation of all DPS, the potential vector values within the whole workspace are determined and other electromagnetic quantities can be derived from the potential vector. The DPSM modeling of the configuration is shown in the Fig. 2. The loop antenna is modeled by a series of N_s DPS, which are noted J_{S1} (and J_{S2} if a second loop coil is considered). The interface 1 is modeled by N_a virtual DPS J_{A1} and J_{A2} and the interface 2 is modeled by N_b DPS denoted J_{B2} and J_{B3}. Then we assemble all the contributions of all the DPS (active and virtual) in the workspace, according to:

$$C = M \cdot J \tag{2}$$

where M expresses the radiation of the DPS, J gathers the intensity of the DPS (known or unknown) and C is the vector of boundary conditions, expressed in Eq. (3), where $\vec{A}$ is the potential vector

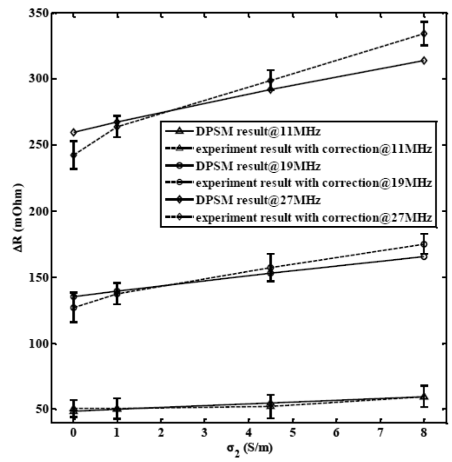


Figure 3: Relation between the conductivity σ_2 in the inclusion and ΔR.

and the indication 1 and 2 represent medium 1 and 2, respectively.

$$\begin{cases} \vec{A}_1 = \vec{A}_2 \\ \frac{1}{\mu_1} \cdot \frac{\partial \vec{A}_1}{\partial \vec{n}} = \frac{1}{\mu_2} \cdot \frac{\partial \vec{A}_2}{\partial \vec{n}} \end{cases} \tag{3}$$

The intensity of all DPS in the workspace can be provided by the numerical inversion of matrix M, and then the magnetic field in the whole workspace can be obtained from the radiation of all the DPS. Finally, the impedance of the loop sensor is given by Eq. (4) in which Φ is the magnetic flux through the loop antenna, ω is the pulsation.

$$Z = \frac{d\Phi}{dt} = j\omega\Phi \tag{4}$$

3. MODELING IMPLEMENTATION AND EXPERIMENTAL VALIDATION

In the simulation with only one coil J_{S1}, the observation points number is $N_p = 10000$. The excitation DPS number $N_s = 100$ while the interface DPS number $N_a = N_b = 2000$. We successively set the conductivity σn the inclusion to $\sigma_2 = 0.003\,\mathrm{S/m}$ (pure water), $1\,\mathrm{S/m}$, $4.5\,\mathrm{S/m}$ and $8\,\mathrm{S/m}$ while the conductivity σ_1 is maintained at $4.5\,\mathrm{S/m}$. The distance d_1 and d_2 are set at $d_1 = 2\,\mathrm{mm}$ and $d_2 = 4.1\,\mathrm{cm}$ respectively. Using the DPSM implemented at 11, 17 and 29 MHz, and using Eq. (4) and Eq. (1), we can get the relation between ΔR and σ_2 shown in Fig. 3.

The obtained computed results are compared to the experimental results obtained in the same configurations. One can note that ΔR is proportional to the changes of conductivity σ_2 in the inclusion for all the frequencies. In addition, there is a good agreement between experiments and computed results, once a multiplicative correction factor of 1.5 has been added to the experimental data. This may be attributed to the fact that the tank used in the experiments is not large enough to fit with the semi-infinite workspace that is assumed in the model. Nevertheless, it can be concluded that DPSM is able to model the electromagnetic coupling between the RF antenna and a dielectric medium including a dielectric inclusion.

4. MODELING TWO-COIL CONFIGURATION FOR THE LOCALIZATION OF DIELECTRIC INCLUSION

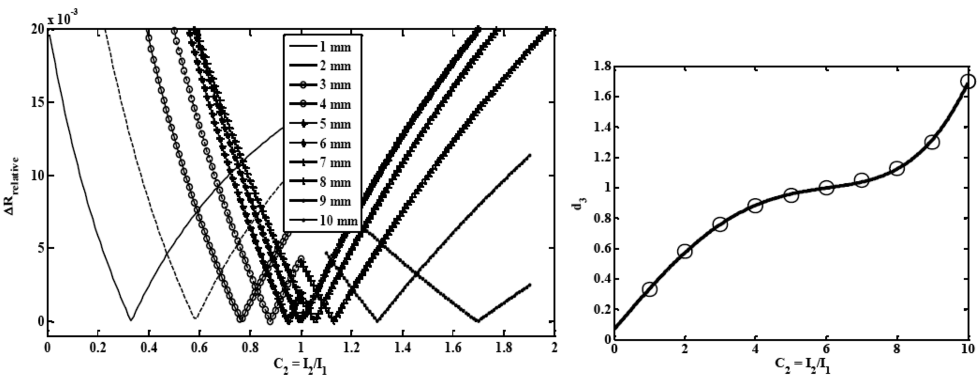
A simple two RF loop antennas system is considered in this section to locate the dielectric inclusion. We consider a second loop coil J_{S2} placed next to J_{S1} (Fig. 1). The observation points number is now $N_p = 20000$. The excitation DPS number is $N_s = 100$ while the interface DPS number are $N_a = N_b = 500$ in the computations. We set $d_1 = 2\,\mathrm{mm}$ and $d_0 = 2\,\mathrm{mm}$. The radius of the loops are $R = 5\,\mathrm{mm}$. The radius of the inclusion is $r = 3\,\mathrm{mm}$ and the distance between the center of the inclusion and the interface 1 is $d_2 = 4\,\mathrm{mm}$. The proportion of the amplitudes between the two loops $C_2 = I_2/I_1$ is ranging from 0.01 to 10, inducing a variation of the induced magnetic field distribution in the area of the inclusion, enabling to “scan” the vicinity of the two-coil system.

With the help of the simulation, we calculate the relative differential resistance of the two coils defined in Eq. (5) where R_1 and R_2 are the resistance of coil 1 and 2.

$$\Delta R_{relative} = (R_2 - R_1)/R_1 \tag{5}$$

Changing C_2 induces changes of the $\Delta R_{relative}$ which exhibits a minimum value, denoted $\Delta Rr_{\min}$, which also depends on the position d_3 of the inclusion, as presented in Fig. 4. So we can establish a relation between $\Delta Rr_{\min}$ and C_2 for different values of d_3. Moreover, we can establish a relation between the position of the inclusion d_3 and the proportion C_2 (Fig. 4(a)). As a result, the position of the inclusion may be detected by changing the values of C_2 and reading out the values taken by the differential impedance.

In this simple case, the horizontal position of the inclusion between the two antennas is determinated. If we add the other coil antennas in the other direction to compose an array of antennas, we may find a way to locate the position of the inclusion in a two dimensional workspace.



(a) (b)

Figure 4: (a) Relation between $\Delta R_{relative}$ and C_2. (b) Relation between the inclusion position d_3 and C_2.

5. CONCLUSION

In this study we have established that DPSM appear to be suitable for the modeling of the electromagnetic coupling between RF loop antennas and a dielectric medium including a dielectric inclusion. In addition, a system constituted of two coil antennas was studied using DPSM to localize the inclusion in a one-dimensional research space. Further works will focus on the modeling and design of antenna arrays suitable for the localization of inclusions in a three dimensional workspace. Furthermore, the modeling of more complex antennas such as multi-turn transmission line resonators [9] will be considered for the design of high sensitivity single or multi-antenna sensing devices.

REFERENCES

1. Isaksson, S. and U. Sapere, "Characterization of meat using dielectric spectroscopy," *Proceedings of the 10th Conference on Electromagnetic Wave Interaction with Water and Moist Substances, ISEMA 2013*, Weimar, Germany, September 25–27, 2013.
2. Hayashi, Y., N. Miura, N. Shinyashiki, et al., "Free water content and monitoring of healing processes of skin burns studied by microwave dielectric spectroscopy in vivo," *Physics in Medicine and Biology*, Vol. 50, No. 4, 599, 2005.
3. Ryynanen, S., "The electromagnetic properties of food materials: A review of the basic principles," Vol. 26, 409–429, 1995.
4. Gabriel, C., *Dielectric Properties of Biological Materials*, Taylor & Francis, 2006.
5. Raicu, V., N. Kitagawa, and A. Irimajiri, "A quantitative approach to the dielectric properties of the skinm," *Physics in Medicine and Biology*, Vol. 45, No. 2, L1, 2000.
6. Peyman, A., "Dielectric properties of tissues; variation with age and their relevance in exposure of children to electromagnetic fields; state of knowledge," *Progress in Biophysics and Molecular Biology*, Vol. 107, No. 3, 434–438, 2011.

7. Sill, J. M., and E. C. Fear, "Tissue sensing adaptive radar for breast cancer detection experimental investigation of simple tumor models," *IEEE Transactions on Microwave Theory and Techniques*, Vol. 53, No. 11, 3312–3319, 2005.
8. Li, X., S. Hagness, B. D. Van Deen, and D. van den Weide, "Experimental investigation of microwave imaging via space-time beamforming for breast cancer detection," *Proc. of the IEEE International Microwave Symposium*, Vol. 1, 379–382, 2003.
9. Masilamany, G., P.-Y. Joubert, S. Serfaty, B. Roucaries, and P. Griesmar. "Wireless implementation of RF probes for dielectric characterization of biological tissues," *IEEE MeMeA*, 1–6, Lisbon, Portugal, June 11–12, 2014.
10. Placko, D. and T. Kundu, "Advanced magnetodynamic and electrodynamic problem" *DPSM for Modeling Engineering Problems*, John Wiley & Sons, Inc., Hoboken, New Jersey, 2007.
11. Kraichman, M. B. and B. Martin, "Impedance of a circular loop in an infinite conducting medium," *J. Res. Nat. Bureau of Standards, D. Radio Propagation*, Vol. 66, No 4, 499–503, 1962.