Accuracy of Bio-Electromagnetic Characterisation and Computation

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Abstract— Evaluation of the induced effects of electromagnetic fields in the human body requires firstly good knowledge of the electrical properties of tissues and secondly efficient computing tools. Firstly, the accuracy of a usual characterisation method is studied using a 3D Finite Element model coupled to electrical circuit equations. It is shown that the relative errors on the measured conductivity and permittivity are respectively 2% and 15% on the 10Hz-10MHz frequency range. Then, the accuracy of the numerical computing of induced fields is studied using various Finite Element formulations applied to a 2D canonical problem. It is shown that a high frequency formulation together with efficient boundary conditions gives the best results on the whole 10Hz-10GHz frequency range.

Index Terms— Bio-electromagnetics, characterisation, induced field computing, Finite Element Method.

I. INTRODUCTION

Electrical characterisation of tissues and induced electromagnetic field computing are required in the study of electromagnetic bio-effects [1]. On one hand, electrical characterisation of biological tissues is difficult due to the tissue conditioning and the measurement method. While the influence of tissue conditioning must be studied experimentally, the accuracy of the measurement method can be evaluated using electromagnetic models. On the other hand, induced electromagnetic field computing is difficult due to the unusual values of the electrical properties of biological tissues. The accuracy of the computing method can be evaluated by analysing the error with respect to the analytical solution of a canonical representative problem.

II. BIO-ELECTRICAL CHARACTERISATION

Different measurement methods are usually used in spectroscopic characterisation of biological tissues:

- In low frequency, the methods consist in impedance measurements using 2 or 4 electrode probes,
- In high frequency, the methods consist in reflection/transmission coefficient measurement using wave guides or coaxial probes.

In this article, the accuracy of a 4 electrode method is studied using an advanced model of the measurement system.
A. Measurement system

The 4 electrode system is commonly used for the characterisation of biological tissues. This system allows to measure the impedance of the tissue on a wide frequency range (10Hz-10MHz). The conductivity and the permittivity are then extracted from the measured impedance. The system is composed of the tissue sample, the probe, the electronic interface and the gain-phase analyzer (Fig.1).

Fig. 1. Four electrode measurement system.

Two uncontrolled elements affect the measurement:

1) The interface impedances: These impedances appear at the electrode/sample interface where the electronic current in the electrode is converted into ionic current in the sample. Ions and electrons form a double layer which thickness is of the order of 5 nm. This localised phenomenon results in an equivalent impedance which is crucial in the lower part of the frequency range. It can be modelled by a constant phase element [2]:

\[ Z_i = K(i\omega)^\beta \]  

2) The parasitic capacitances: These capacitances result from electrodes and wires coupling and from the internal capacitances of the electronic devices. Their influence is large in the higher part of the frequency range.

B. Finite Element model coupled to electrical equations

In order to evaluate the accuracy of the measurement system, an advanced model is developed. This model takes into account both the interface impedances and the parasitic capacitances. The sample and the immersed part of the electrodes are modelled with the finite element method. The electric potential (V) in the sample is computed using the electro quasi static formulation with appropriate conditions on the boundaries. Interface impedances (z, \(\Omega \text{m}^2\)) are modelled applying boundary impedance conditions on the surface of the electrodes [3]:

\[ V_{\text{sample}} - V_{\text{electrode}} = z(\sigma + i\omega\varepsilon)\nabla V\hat{n} \]  

(2)
The electrical circuit represents the parasitic capacitances and the generator. The voltage and the current in each electrode \((V_m, I_m, V_i, I_i)\) verify the Kirchhoff’s laws associated with the electrical circuit. The computation domain is limited to one quarter of the sample taking advantage of the symmetry of the system (Fig. 2).

![Finite element model and coupled electrical circuit.](image)

The parameters of the model are determined from experimental measurements:

- The parasitic capacitances are determined from open measurements,
- The interface impedances depend on the studied sample and cannot be determined for an unknown sample. Nevertheless, values of the interface impedances are measured for known KCL solutions which are representative of biological media (Table I).

### Table I. KCL solutions and interface impedances

<table>
<thead>
<tr>
<th>Concentration (mol/L)</th>
<th>Conductivity (S/m)</th>
<th>Relative Permittivity</th>
<th>(\beta)</th>
<th>(K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.005</td>
<td>0.0637</td>
<td>81.4</td>
<td>0.826</td>
<td>1.20 105</td>
</tr>
<tr>
<td>0.01</td>
<td>0.129</td>
<td>81.4</td>
<td>0.833</td>
<td>1.17 105</td>
</tr>
<tr>
<td>0.02</td>
<td>0.248</td>
<td>81.4</td>
<td>0.874</td>
<td>1.30 105</td>
</tr>
</tbody>
</table>

C. Accuracy of the measurement system

Simulations are done on a muscle sample with known electrical properties [4]. The interface impedance parameters are arbitrarily chosen in accordance with the measurements on the KCL solutions: \(\beta = 0.8\) and \(K = 1.59\ 10^5\). The conductivity and the permittivity of the sample under test are extracted from the computed complex impedance \((Z)\) and the probe constant \((C)\):

\[
\sigma + i\omega \varepsilon = C/Z
\]

(3)

Bao’s calibration method [5] is used to correct the computed impedance. Three KCL solutions
(Table 1) are used as reference samples for the calibration.

The interface impedances and the parasitic capacitances induce modifications of the distribution of the potential in the sample (Fig.3):

- at 10Hz (left), where the interface impedances reach high values, the equipotential lines are not parallel to the electrodes;
- at 10MHz (right), where the parasitic capacitances have a great influence, the potential of the voltage measurement electrode is low;
- at 100kHz (middle), where there is no significant influence of neither the interface impedances nor the parasitic capacitances.

Fig. 3. Electric potential in various cut planes in the sample, at 10Hz, 100kHz, and 10MHz.

In consequence, the probe constant becomes frequency dependent and the accuracy of the measurement is affected. As these parameters are uncontrolled and depend on the studied sample, they cannot be efficiently corrected by the calibration method. The simulations show that the conductivity and the permittivity can be evaluated, respectively, with 2% and 15% accuracy using the measurement system (Fig.4).
III. INDUCED FIELDS COMPUTING

Several numerical techniques are usually applied to induced electromagnetic fields computation in the human body: the impedance method [6], the finite difference method (FDTD) [7], the boundary element method [8] and the finite element method (FEM) [9]. They are applied to solve Maxwell’s equations using different assumptions depending on the frequency range of the sources. These assumptions result in different numerical formulations:

- In the low frequency range, the effects of the magnetic field and the electric field are computed separately and then summed [10].
- In the high frequency range, the wave equation is considered using different conditions on the domain boundaries.

In this article, the accuracy of several FEM formulations is studied considering a 2D canonical problem.

A. 2D canonical problem

The considered 2D canonical problem is the scattering of a plane wave by concentric cylinders filled with biological tissues [4]. The diameter of the cylinder is representative of the human body. The thickness of the different layers is representative of the organ heterogeneities. The analytical solution [11] allows to evaluate the accuracy of the numerical formulations.

B. FEM formulations of the problem

Computing induced electromagnetic quantities in the human body using the FEM requires specific constraints: the mesh has to be dense enough to take the organ heterogeneity into account, and the studied domain has to be limited to avoid computational overload. In consequence, the exterior boundaries are chosen to be close to the cylinder (Fig. 5).
Several formulations are considered (Table 2):

- For the low frequency formulation (LF), the resulting electric field is the sum of the electric field computed using the electro quasi static (Dielectric) formulation and the electric field computed using the electrodynamic formulation;
- The high frequency formulation (HF) consists in solving the wave equation associated with different boundary conditions (transparent condition HFTC, absorbing boundary condition HFAB1, homogeneous Dirichlet condition HFD0 and perfectly matched layers HFPML).

<table>
<thead>
<tr>
<th>TABLE II. FEM FORMULATIONS</th>
</tr>
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<tbody>
<tr>
<td>HF</td>
</tr>
<tr>
<td>Wave</td>
</tr>
<tr>
<td>Unknown:</td>
</tr>
<tr>
<td>Equation:</td>
</tr>
<tr>
<td>Source:</td>
</tr>
<tr>
<td>Boundary condition:</td>
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C. Accuracy of the computational method

An average relative error on the magnitude of the electric field is calculated over the whole cylinder, on the 10Hz-10GHz frequency range (Fig.6).
It is shown that HF formulations with correct boundary conditions (PML or Transparent conditions) give the best results over the whole frequency range, even in low frequency. Compared to PML, the use of transparent conditions (coupling with a boundary element method [12]) is slightly less efficient, for frequencies higher than 100MHz, since the mesh density must be lowered to avoid computational overload. The HF formulation using first order absorbing boundary conditions is a simple and efficient formulation above 200MHz. For lower frequencies, the first order absorbing boundary condition induces undesired reflections since the distance between the boundary and the cylinder is small compared to the wavelength. Below 40MHz, using a simpler formulation such as HFD0 gives better results. The LF formulation is of course useless for high frequencies. More unexpected, the LF formulation is shown to be not very efficient for low frequencies. The inaccuracy of the LF formulation is principally due to the representation of the source of electric field. The boundary of the computational domain where the Dirichlet boundary condition is used to impose the electric potential is too close to the body to represent accurately the incident electric field. Enlarging the computational domain for the dielectric formulation allows great improvement of the accuracy (Fig. 7).

This analysis shows that induced fields computing in the human body is an unusual electromagnetic
problem (high mesh density in the body and close boundaries to reduce the computational domain) which requires a careful choice of the numerical formulation to use.

IV. CONCLUSION

Some of the difficulties of bio-electromagnetics are analysed by solving discrete problems [13]. These difficulties come from both the electrical characterisation method and the computational method. Considering the electrical characterisation method, two particularities of biological tissues affect the accuracy of the measurement:
- The effect of interface impedances which cannot be completely removed, even using a 4 electrode method;
- The influence of parasitic elements which is important when measuring high impedances.

Considering the computational method, difficulties are due to the unusual electrical properties of biological tissues, the need for high mesh density in the body and the need to limit computational domain. Using the FEM, it is shown that high frequency formulations are required to obtain high accuracy.

In the area of bio-electromagnetics the accuracy of the measurement and computational methods must be carefully evaluated in order to obtain reliable results. Accuracy study will also be used to optimise the geometry of the characterisation probe, to make it less sensible to the uncontrolled elements. Accuracy study of the computational method will be extended to more realistic 3D problems.

REFERENCES