Optimization of a Four-Electrode Probe for the Electrical Characterization of Biological Tissues

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Abstract — Four-needle probes are widely used for the electrical characterization of biological tissues between 10Hz and 10MHz. The measurement accuracy depends strongly on the electrode/sample interface impedance in low frequency and on the parasitic capacitances of the measurement system in high frequency. Using a finite element model coupled with a deterministic optimization algorithm, it is shown that the geometry of the probe should be different at 10Hz and 10MHz to improve the performances of the measurement system.

I. Introduction

The electrical characterization of biological tissues in the 10Hz-10MHz frequency range is generally based on four electrode impedance measurements. At pulsation (ω), the conductivity (σ) and the permittivity (ε) of the tissue are calculated from the measured impedance (Z) and the probe constant (K) using equation (1):

$$\sigma + i\omega\varepsilon = K/Z \, . \qquad (1)$$

The probe constant is often considered to depend only on the geometry of the probe. It depends actually also on the frequency, on the measurement system and on the properties of the studied sample: the electrode/tissue interface impedances and the parasitic capacitances of the measurement system may have great influence. The interface impedances appear at the surface of the electrodes where the electronic current is converted into ionic current in the sample. The parasitic capacitances are principally located in the electronic components of the measurement system. These elements generate modifications of the electric potential distribution [1] in the sample with frequency, leading to measurement errors which cannot be removed using usual calibration methods.

A four aligned needle electrode probe is studied. The four-electrode probe impedance is the ratio of the voltage measured on the interior electrodes with the current injected on the exterior electrodes. The four-electrode probe may also be used to perform two-electrode measurements. In this case, the corresponding two-electrode probe impedance is measured on the exterior electrodes. A finite element (FE) model coupled with a deterministic optimization algorithm is used to find the best configurations of electrodes so that the measurement accuracy is improved.

II. Optimization of the Four-Electrode Probe

The electrodes and the sample are modeled using FE [2]. Interface impedances are taken into account using an impedance condition on the surface of the electrodes. The corresponding impedance is modeled by a constant phase element [3]:

$$Z_i = A(i\omega)^{-\beta} \, . \qquad (1)$$

The model is coupled to the equations of the electrical circuit representing the parasitic capacitances. Taking advantage of the symmetries of the system, only one quarter of the geometry is represented (Fig. 1). The parasitic capacitances (C_{mm} and C_{im}) are determined from open measurements. Representative values of the parameters of the interface impedance (A and β) are determined from measurements on KCl solutions. The length and spacing of the electrodes (X_1, X_2, X_3, X_4 in fig. 1) are the optimization parameters. A deterministic technique based on the steepest descent method together with a golden section line search is used [4]. The objective function is given by

$$Obj_f(X) = \left|\rho(f) - \rho_{true}(f)\right| , \qquad (2)$$

where X represents the optimization parameters, f is the frequency in Hertz, ρ and ρ_{true} are, respectively, the measured resistivity and the true complex resistivity of the sample ($\rho = (\sigma + i\omega\varepsilon)^{-1}$). For each optimization step, a simulation without interface impedances and parasitic capacitances is first performed in order to compute the four-electrode probe constant. A simulation with the complete model is then performed to compute the measured four-electrode impedance. The optimization domain is defined taking into account technical constraints (minimum spacing, probe dimensions).

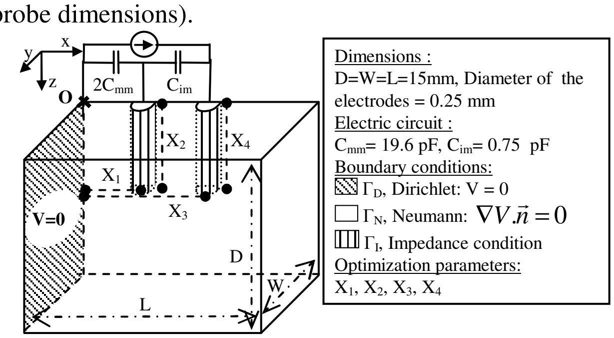

Fig. 1. Finite element model of the measurement system.

The probe is optimized separately for 10Hz and 10MHz measurements. As the results may depend on the properties of the studied sample, the optimization is realized using representative values of conductivity and permittivity (Table I). The electrode configurations (Fig. 2) found for a sample having typical properties (bolted in Table I) are considered in the following.

TABLE I
OPTIMIZED PARAMETERS

Conductivity (S/m)	Permittivity	A (interface impedance)	X_1 (mm)	X_2 (mm)	X_3 (mm)	X_4 (mm)
10Hz optimization						
0.01	10^2	0.1	1.2	1.2	5.4	1.4
0.1	$\mathbf{10^5}$	**0.1**	**1.5**	**1.2**	**5.6**	**1.0**
1	10^8	0.1	1.4	1.0	5.7	1.2
10MHz optimization						
0.1	10	0.1	0.7	4.5	5.8	1.2
0.8	$\mathbf{10^2}$	**0.1**	**0.7**	**4.9**	**5.8**	**1.4**
2	10^3	0.1	0.7	4.9	5.8	1.3

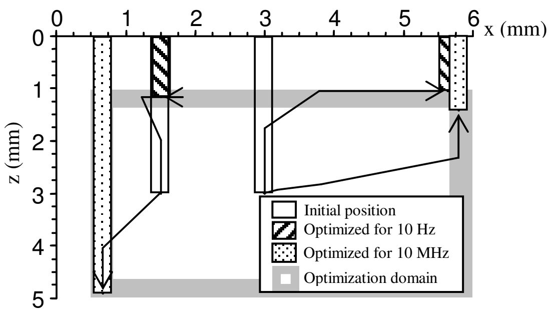

Fig. 2. Electrode configurations before and after optimization.

III. Simulation of Measurement with Initial and Optimized Probes

In order to evaluate the accuracy of the optimized probe, a 10Hz-10MHz characterization of a muscle sample is simulated. The sample has frequency dependant electrical properties [5], and the interface impedance parameters are A=0.1 and β=0.8. Three simulations on ionic solutions samples are used as references and a usual calibration method [6] is applied to the measured impedances. Four results of simulation are compared: four-electrode measurements with the initial probe (1), four-electrode measurements with the optimized probe at 10Hz (2) and 10MHz (3), and two-electrode measurement with the 10Hz optimized probe (4). The relative error on the measured conductivity and permittivity is computed with respect to the values used in the model (Fig. 3 and Fig. 4).

The probe optimized for 10MHz gives good results on the 100kHz-10MHz frequency range but is not accurate below 100kHz. The probe optimized for 10Hz gives the best results on the 10Hz-100kHz frequency range and the corresponding two-electrode measurement gives good results on the 100kHz-10MHz frequency range.

IV. Conclusion

Electrical characterization of biological tissues is a difficult area of impedance measurement. Usual calibration methods cannot remove efficiently the measurement inaccuracies induced by the interface impedances and the parasitic capacitances. In consequence, it is interesting to reduce the measurement inaccuracy by optimizing the probe. It is done using an optimization algorithm coupled with a FE model of the measurement system. In this paper, it is shown that a probe optimized for 10Hz should give accurate results on the whole 10Hz-10MHz frequency range: four-electrode measurements are used below 100kHz and two-electrode measurements are used above 100kHz. In the future, this work will be extended to other types of probe.

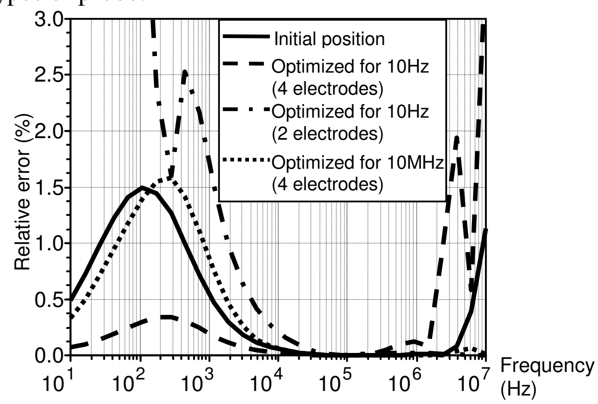

Fig. 3. Relative error on the conductivity.

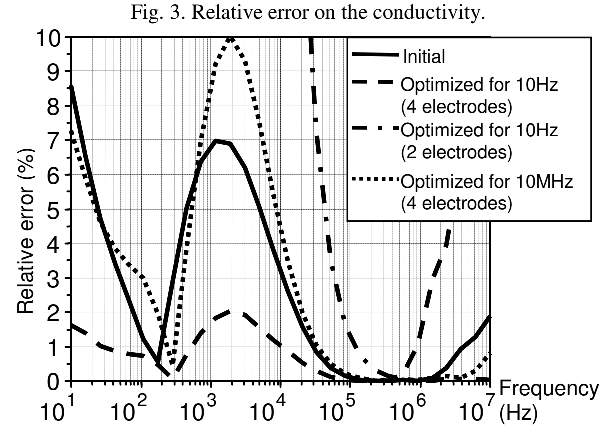

Fig. 4. Relative error on the permittivity.

V. Acknowledgment

The authors would like to thank the Région Rhône-Alpes for the financial support, the CNPq (350.320/2004-7) and the FAPEMIG (TEC 905/2003).

VI. References

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