Optimal Interdigitated Electrode Sensor Design for biosensors using Differential Evolution Algorithm

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Abstract. Optimization of interdigitated electrode sensor design is essential for practical impedance spectroscopy in the medical and pharmaceutical fields because of their easy fabrication procedure and inexpensive. The geometry presents a prospective for ameliorating sensitivity over other microelectrode designs. The geometric optimization of a sensor's structure with interdigital electrodes is one of the difficult optimization problems. To solve this type of problem, we use metaheuristic methods to find the optimal solution. The method chosen in this paper is the differential evolution algorithm DE, which is widely used to solve the overall optimization problem. We will optimize the geometrical parameters of the interdigitated electrodes by minimizing the F_{Low}, the proper band [F_{Low}<-->F_{High}] using MATLAB script, the validity of the obtained results is investigated using ADS tools

1 Introduction

Nowadays, there are many biomedical applications based on electrical impedance spectroscopy [1]. It is a commonly used medical field technique with better than 60 years of applications in clinical studies or research. Bioimpedance spectroscopy compares a biological medium's electrical response to an external electrical excitation varying in time [2]. This non-invasive technique provides access to an electrical characterization of living organisms as a method of measuring variations (structure and composition of biological tissues) linked to changes generated by physio pathological processes. It allows to determine tissues' physiological state ex vivo or directly on biological organs by their electromagnetic characterization. Electromagnetic characterization of biological media based on bioimpedance using microelectrode measurement techniques is becoming an essential diagnostic tool for the study of electrophysiological and biophysical transformations due to viral illnesses, cancer detection [3], and pharmaceutical quality control. This paper's main objective is to design a biosensor to characterize biological media by impedance spectroscopy. More precisely, the geometrical optimization of its interdigitated electrode structure. This optimization permits widening the frequency range of measurement. Remind us that the sensor's optimization is one of the numerous delicate steps in realizing a bioimpedance measurement instrument.

2 Overview of Deferential evolution algorithm (DE)

In the DE method, the initial population is generated by uniform random selection over each variable's set of possible values. The user specifies the lower and upper bounds of the variables according to the nature of the problem. After initialization, the algorithm performs a series of transformations on the individuals in a process called evolution. In general, the process of the DE algorithm can be summarized, as shown in Fig.1 [4].

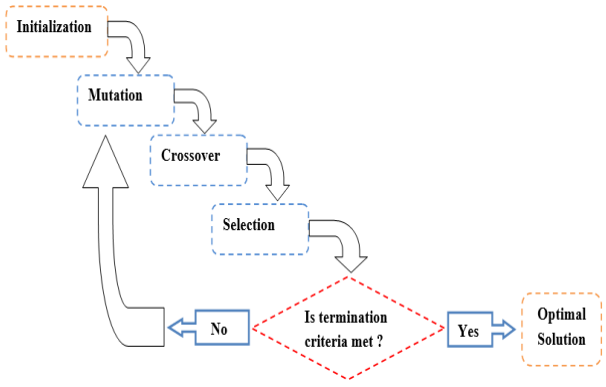

Fig. 1. Flowchart of the basic model of the DE algorithm

3 Biosensors with interdigitated electrodes

Biosensors with interdigitated electrodes have single-plane electrodes and fabricated using a conventional metal deposition [5]. Sensors with interdigital electrodes have been optimized to improve the frequency band and

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developed to detect DNA sequences by impedance spectroscopy and blood analysis. As shown in Fig.2, an interdigital sensor consists of two comb-shaped metal electrodes, each electrode containing a width W, a length L of electrodes, and a space between two consecutive electrodes S.

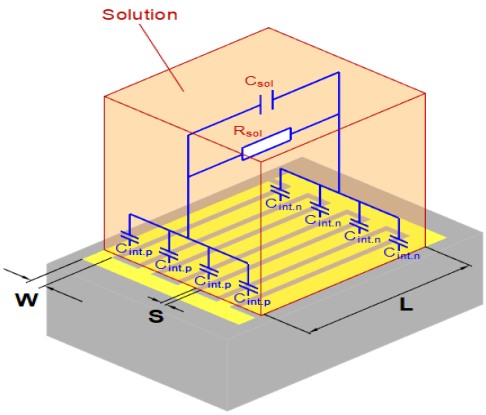

Fig. 2. Similar circuit model of IDEs in a liquid environment

The principle of operation of an interdigital electrode sensor is similar to the parallel plate capacitor. The sensor is deposited on a substrate, and an electric field is generated by applying a voltage between the two electrodes. When a biological element is placed on the sensor, the electric field passes through this biological element [6]. Dielectric properties of the biological fluid and the geometry of the object to be measured impact the capacitance and conductance between the two electrodes. The electric field difference is used to define the effects of the biological environment relying on the application.

3.1 Equivalent electrical circuit model

The elements of the equivalent model can be expressed in terms of physical and electrical quantities, as showing in Fig.3 [7].

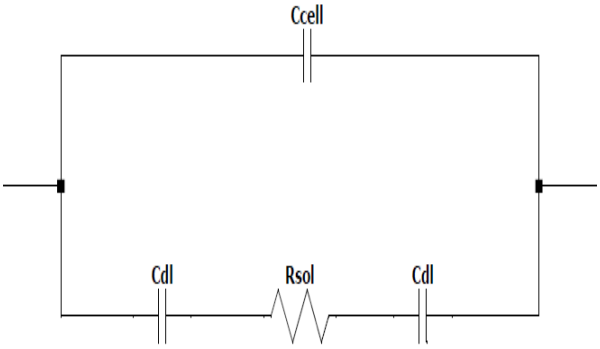

Fig. 3. Equivalent electrical circuit model

R_{sol} Refers to the resistance of the electrolyte solution or also the impedance modulus, it models the conductive effects of the medium beneath the effect of an electric field. This component is the sensitive element of the measurement. It is related to the conductivity of the electrolyte medium σ_{Sol}, and the cell factor K_{Cell} according to the following expression [8]:

$$R_{sol} = \frac{K_{Cell}}{\sigma_{Sol}} \quad (1)$$

With:

$$K_{Cell} = \frac{2}{(N-1)L} \frac{K(k)}{k(\sqrt{1-k^2})} \quad (2)$$

$$K(k) = \int_0^1 \frac{1}{\sqrt{(1-t^2).(1-k^2t^2)}} dt \quad (3)$$

$$k = \cos\left(\frac{\pi}{2}.\frac{w}{s+w}\right) \quad (4)$$

N indicates the number of electrodes, S representing the spacing between two consecutive electrodes, W corresponds to the width of an electrode, and L refers to the length of an electrode.

C_{cell} corresponds to the Capacitance models the dielectric part of the medium under test. It represents the direct capacitive coupling between the two electrodes. This capacitance is related to the dielectric permittivity by:

$$C_{cell} = \frac{\varepsilon_0 \varepsilon_{r\,sol}}{K_{cell}} \quad (5)$$

$$\varepsilon_{r\,sol} = \varepsilon_{r\,water} = 80 \quad (6)$$

The impedances describing the interface effects produced at the electrode-electrolyte interfaces are facilitated by the double-layer capacitance C_{dl}. These impedances are dependent on the type of material making up the electrodes and the electrolyte solution.

The capacitance that models the dielectric part of the medium under test means the unpretentious capacitive coupling between the two electrodes. This capacitance is related to the dielectric permittivity by:

$$C_{dl} = 0{,}5.A.C_{dl,Surface} = 0{,}5.w.L.N.C_{dl,Surface} \quad (7)$$

A is the total electrode surface area. The factor of 0.5 corresponds to a single capacitance C_{dl}, which is determined by half of the two interface capacitances resulting from the interface effects at the total electrode surface. In the case of interdigitated electrodes, this surface is equal to the electrode length multiplied by their width multiplied by the number of electrodes.

The characteristic double layer capacity C_{dl}, Surface is assumed to be equal to Stern's characteristic double layer capacity for electrolyte environments with a very high ionic concentration, C_0 = 0.047 F/m2.

From the equivalent electrical circuit Fig.3, the total impedance observed can be expressed as:

$$Z(jw) = \frac{Z_1}{j.w.C_{cell}.Z_1+1} \quad (8)$$

With:

$$z_1 = R_{Sol} + \frac{2}{j.w.C_{dl}} \quad (9)$$

The C_{dl} double-layer capacitance shows a mainly capacitive phenomenon at frequencies lower than Flow (the low cut-off frequency). As a result, the impedance Z_{dl} from the double layer is much higher than the resistance R_{Sol} and donates mostly to the total impedance value Z.

The impedance decreases with increasing frequency up to F_{low}. However, above the cutoff frequency F_{low}, the double-layer capability does not intervene in the total impedance. The reason is that only the resistance R_{Sol} (or modulus of the total impedance) acts on impedances lower than F_{high}, and C_{cell} is not yet indicative. In this frequency range limited by Fl_{ow} and F_{high}, the total impedance is independent of the frequency.

In this range, an actual result of the exact measurement of the biological sample is derived from the observed impedance based on the total impedance (e.g., the conductivity, which can be calculated from the R_{Sol} value). We can conclude that to increase the frequency measurement's sensitivity. We need to widen the frequency range in the dominant impedance spectrum of the R_{Sol} module. By extending the frequency range (called the useful frequency range), the interface phenomena represented by the double layer capacitance eliminated and achieved by shifting the low cut-off frequency Flow as low as possible.

- ✓ For the low frequencies $f < F_{Low}$:

The total impedance depends only on the double layer capacity C_{dl}.

$$Z_1(f) = R_{Sol} + \frac{2}{j.\omega.C_{dl}} \quad (10)$$

$$Z_{1\,total}\ (f) = \frac{1}{N}\left(\frac{K_{cell}}{\sigma_{Sol}} + \frac{2}{j.\pi.f.A.C_{Stern,Surface}}\right) \quad (11)$$

- ✓ For the band $F_{Low} \leq f \leq F_{High}$:

The impedance turns on the resistance of the medium.

$$Z_{2\,total}\ (f) = \frac{R_{sol}}{N} \quad (12)$$

- ✓ For the high frequencies $f > F_{High}$:

The impedance depends on the C_{cell} capacity of the cell

$$Z_{3\,total}\ (f) = \frac{1}{N}\frac{R_{sol}}{1+j.2\pi.f.C_{Cell}.R_{sol}} \quad (13)$$

We are interested in the frequency band limited by F_{Low} and F_{High}.

$$F_{Low} = \frac{\sigma_{Sol}}{0.5.\pi.w.L.N.C_{DL\ Surface}.K_{Cell}} \quad (14)$$

$$F_{High} = \frac{\sigma_{Sol}}{2.\pi.\varepsilon_0.\varepsilon_{r\ Sol}} \quad (15)$$

3.2 Formulation of the optimization problem

We will optimize our geometrical structure of the interdigital electrode by minimizing F_{Low}, which means enlarging the proper band [F_{Low}<-->F_{High}]. Therefore, our objective function to be minimized will be provided by equation (14). The values of the constants used are shown in Table 1, and the constraints on the limits of variation of the problem parameters are presented in Table 2.

Table 1.Values of the constants used

Constant	Value
σ_{Sol}	0.7 S/m
$C_{DL,Surface}$	0.047 F/m²
N	40

Table 2. The geometric constraints

Parameter	VarMin	VarMax
W	Wmin = 10^{-3} µm	Wmax = 100 µm
S	Smin = 10^{-4} µm	Smax = 50 µm
L	Lmin = 0.1 mm	Lmax = 9 mm

The parameters of the DE algorithm are given in Table 3. For the DE algorithm, we have chosen 100 for the number of population and 1000 for the number of iterations, with d=3 numbers of decision variables.

Table 3. The parameters of the DE algorithm

Maxit	nPop	D
1000	100	3

3.3 Optimization result

For interdigital electrode design, the ED algorithm begins by creating initial individuals at random, where each individual is defined by its three genes [W=chrom (:,1), S= chrom (:,2), L= chrom (:,3)], representing the geometrical parameters of the electrode layout, and must respect the limits of the variables Table 3 (Upper and Lower bound). Fig.4 shows the objective function (F_{Low}) as a function of number iterations, while Table 4 represent the optimization result of each parameter.

Table 4. Optimization result

Parameter	Value
W_{opt}	100 µm
S_{opt}	50 µm
L_{opt}	2.84 mm
F_{Low_opt}	46.22 Khz

A robustness test on the cost function has been planned to verify the algorithm's convergence towards the exact optimum. In Fig.5, we show the results obtained from the boxplot.

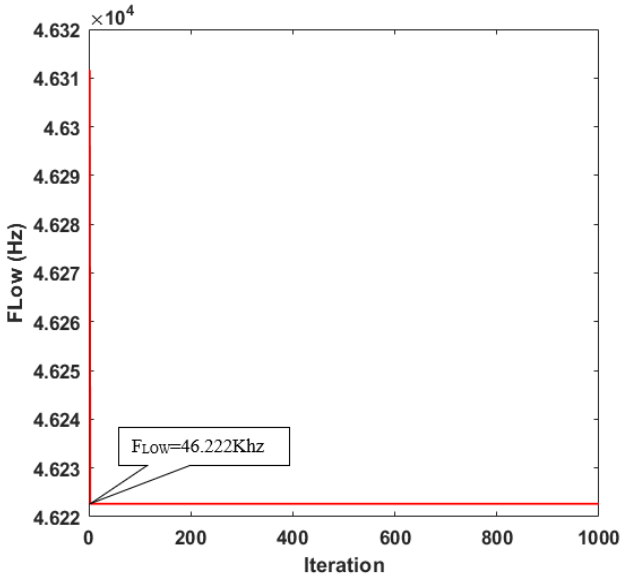

Fig. 4. Result of objective function

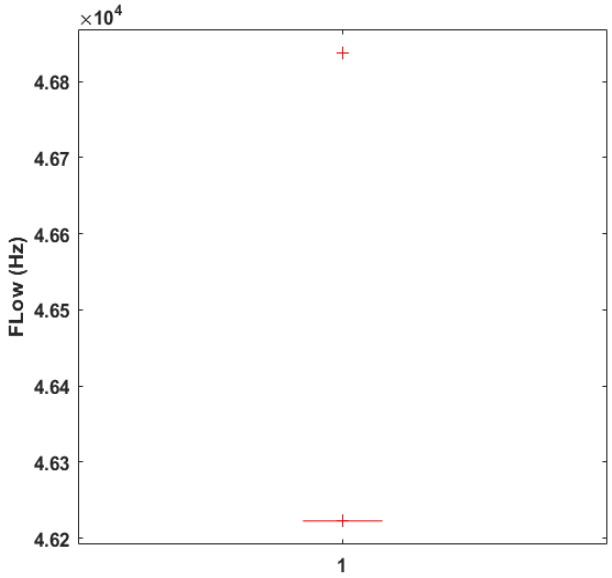

Fig. 5. Convergence of the cost function

The results found show very clearly that the algorithm applied to the cost function converges approximately to 46.22 khz value. In order to confirm the results obtained, we will simulate the circuit model using the Advanced Design System (ADS) tools as showing in the Fig.6. As shown in Fig.7, the simulation result is almost the same result obtained by the DE algorithm with a low error of 0.47%.

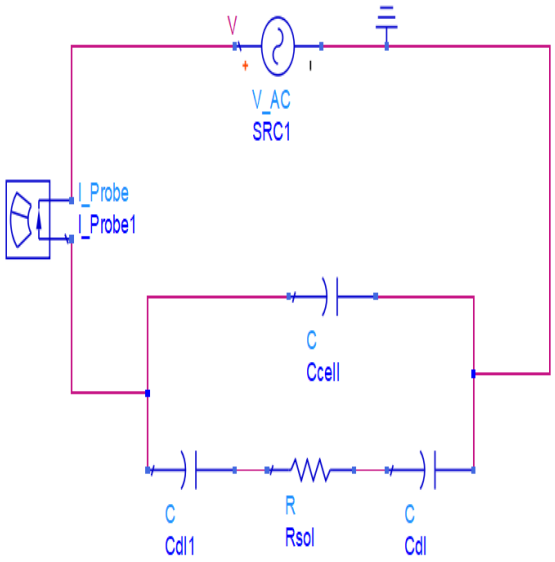

Fig. 6. Circuit model

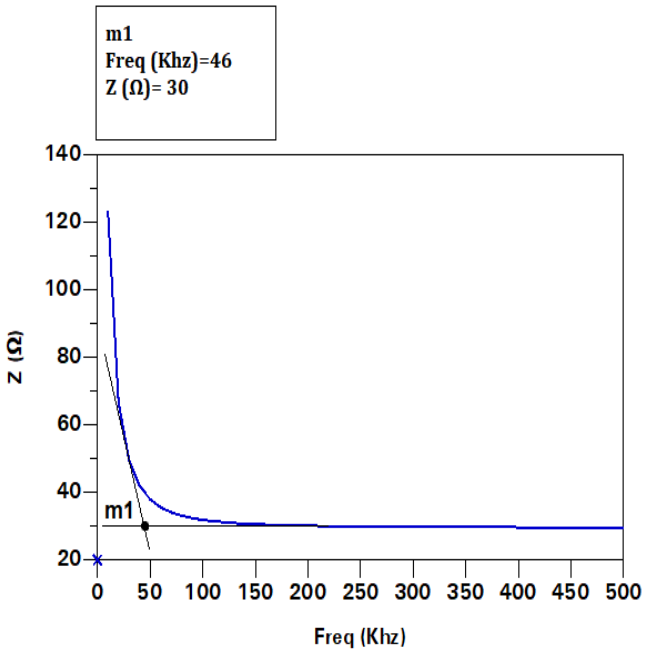

Fig. 7. Impedance z (Ω) vs Frequency (khz)

Table 5 shows the resistance and capacities calculate with the previous equations, using the optimal parameters found by the DE algorithm.

Table 5. Component value of the circuit model

Component	Value
R_{sol}	29.53 Ω
C_{dl}	266.93 nF
C_{cell}	34.26 F

4 Conclusion

We have presented a physical model of an IDE intended to detect DNA sequences by impedance spectroscopy and blood analysis. We have suggested a method to theoretically model and discover the effect of the geometrical parameters of the IDE (Width W, inter-distance S, and some electrodes N) on the valuable band [F_{Low}<-->F_{High}] of the IDE using the Differential Evolution algorithm (DE). The results of the simulations show the advantage of optimizing the components of the sensor. We have built the electrical equivalent circuit components with the optimal obtained results and have discussed its impedance response using ADS. The results of theory and simulation are in full accordance with the concept of the minimum cut-off frequency.

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