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Cole impedance extractions from the step-response of a current excited fruit sample

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ABSTRACT

In the field of bioimpedance measurements the Cole impedance model is widely used for characterizing biological tissues and biochemical materials describing the impedance behaviour as a function of frequency. These measurements give information about the electrochemical processes in tissues and can be used to characterize the tissue or monitor for physiological changes. Traditionally these parameters are extracted using fitting routines on direct measurements of the impedance. Here, a method of non-linear least squares fitting (NLSF) is applied to extract the single and double-dispersion Cole impedance parameters from collected current-excited step response datasets without requiring direct impedance measurements. The impedance parameters are extracted from MATLAB simulations showing less than 1% and 5.5% for the single and double dispersion parameters, respectively, when a 0.5% random noise component is present. This extraction is verified experimentally using apples as Cole impedances showing less than 2% relative error between simulated responses (using the extracted impedance parameters) and the experimental results over the entire dataset.

1. Introduction

Fractional calculus, the branch of mathematics regarding differentiations and integrations to non-integer orders, is a field that is over 300 years old. Its origins dating back to a correspondence from 1695 between Leibniz and L'Hôpital, with L'Hôpital inquiring about Leibniz's notation, $\frac{d^n y}{dx^n}$, and the meaning if $n = 1/2$, and the reply from Leibniz, "It will lead to a paradox, a paradox from which one day useful consequences will be drawn, because there are no useless paradoxes" (Ortigueira, 2011). Time has proven Leibniz quite the prophet as the applications of these fractional integrals and derivatives has seen explosive growth in many fields of science and engineering in the past few decades since publication of the book by Oldham and Spanier dedicated to fractional calculus (Oldham and Spanier, 1974). These applications have appeared in control systems, signal processing, bioengineering, thermal modelling and more. A detailed survey of the major documents and events from the field of fractional calculus from 1974 until the present are given in (Tenreiro Machado et al., 2011). Concepts from fractional calculus have also been migrating into electrical engineering (Ortigueira, 2008; Elwakil, 2010) showing applications including:

- Electronic filter circuits with greater control of the magnitude attenuation characteristics (Maundy et al., 2011).
- Modelling the losses of coils using a fractional impedance (Schafer and Kruger, 2008).
- Generalizing the Smith chart to the fractional domain for plotting and matching fractional impedances in the RF and microwave regime (Shamim et al., 2011).

A fractional derivative of order α is given by the Caputo derivative (Podlubny, 1999) as

$$ {}_{a}^{C}D_t^{\alpha} f(t) = \frac{1}{\Gamma(\alpha - n)} \int_a^t \frac{f^{(n)}(\tau) d\tau}{(t-\tau)^{\alpha+1-n}} \tag{1} $$

where $\Gamma(\cdot)$ is the gamma function and $n - 1 \leqslant \alpha \leqslant n$. We use the Caputo definition of a fractional derivative over other approaches because the initial conditions for this definition take the same form as the more familiar integer-order differential equations. Applying the Laplace transform to the fractional derivative of (1) with lower terminal $a = 0$ yields

$$ \mathcal{L}\left\{ {}_{0}^{C}D_t^{\alpha} f(t) \right\} = s^{\alpha} F(s) - \sum_{k=0}^{n-1} s^{\alpha-k-1} f^{(k)}(0) \tag{2} $$

Therefore it becomes possible to define a general fractance device with impedance proportional to s^{α} (Nakagawa and Sorimachi, 1992) where the traditional circuit elements are special cases of the general device when the order is −1, 0, and 1 for a capacitor,

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resistor, and inductor, respectively. A special case of the general fractance device is referred to as a Constant Phase Element (CPE) which have shown numerous applications in the field of bioimpedance, which measures the passive electrical properties of biological materials. These measurements give information about the electrochemical processes in tissues and can be used to characterize the tissue or monitor for physiological changes (Grimnes and Martinsen, 2000). The impedance of CPE is $Z_{CPE} = 1/(j\omega)^{\alpha}C$ or $1/s^{\alpha}C$ in the s-domain, where C is the capacitance and α is its order. It's name is in reference to the phase angle, ϕ_{CPE}, which is independent of frequency and dependent only on the order, α, given as $\phi_{CPE} = \alpha\pi/2$. While $\alpha \in \Re$ is mathematically possible, the values from experimentally collected data are typically in the range of $0 < \alpha < 1$. These devices have also been called fractional order capacitors, in reference to their order which takes a value between the traditional circuit elements of a resistor and capacitor. It is for this reason that we use a capacitor as the schematic representation of CPEs in this work.

In the field of bioimpedance measurements the Cole impedance model, introduced by Kenneth Cole in 1940 (Cole, 1940), is widely used for characterizing biological tissues and biochemical materials. The single-dispersion Cole model, shown in Fig. 1(a), is composed of three hypothetical circuit elements. A high-frequency resistor R_{∞}, a resistor R_1 and a CPE (C_1, α_1). This model has become very popular because of its simplicity and good fit with measured data, illustrating the behaviour of impedance as a function of frequency. An expanded model, the double-dispersion Cole model, is used to accurately represent the impedance over a larger frequency range or for more complex materials. This model, shown in Fig. 1(b), is composed of an additional parallel combination of a resistor (R_2) and CPE (C_2, α_2) in series with the single dispersion Cole model. The impedance of both models can be described by

$$Z(s) = R_{\infty} + \sum_{i=1}^{n} \frac{R_i}{1 + s^{\alpha_i} R_i C_i} \tag{3}$$

where $n = 1$ and 2 for the single and double dispersion models, respectively. Noting that $s^{\alpha} = (j\omega)^{\alpha} = \omega^{\alpha}[\cos(\alpha\pi/2) + j\ \sin(\alpha\pi/2)]$. The Cole impedance model is not the only available bioimpedance model, an alternative to the single-dispersion Cole impedance was presented in (Grimnes and Martinsen, 2005) that is compatible with the theory of relaxation can also be used.

Physiologically, the resistances in these models are contributed by the numerous intracellular, extracellular,and cellular membrane resistances within the tissue; with capacitance contributed by the membrane capacitances of the numerous tissue cells. The parameter α is a dimensionless quantity known as the dispersion coefficient. It is possible to regard it in several ways, including, as a distribution of relaxation times caused by the heterogeneity of cell sizes and shapes, a measure of the deviation from an ideal capacitor in the equivalent circuit, or as a measure of physical processes like the Warburg diffusion (Grimnes and Martinsen, 2000).

Now, while these models do not provide an explanation of the underlying mechanisms, there has been a large and expanding body of research regarding their use in agriculture including

- Characterizing the tissues of different fruits and vegetables including apples, apricots (Elwakil and Maundy, 2010), plumbs (Maundy and Elwakil, 2012), potatoes, kiwis (Elwakil and Maundy, 2010; Jesus and Tenreiro Machado, 2012), garlic, tomatoes, and pears; with potential to measure the maturity or give an estimate of lifespan for storage purposes (Jesus et al., 2008).
- Relationship between the rooting ability and Cole parameters of shoots and leaves of olive cuttings (Mancuso, 1998).
- Effects of drying and freezing-thawing treatments on eggplant pulp samples (Wu et al., 2007).
- Non-destructive method for detection of incipient mould development on wood surfaces (Tiitta, 2009).
- Fit the impedance data collected from the bark and wood of current and one year old Scots pine shoots (Repo and Zhang, 1993).

To characterize a particular tissue or material using the Cole model requires the determination of the four ($R_{\infty}, R_1, C_1, \alpha_1$) or seven ($R_{\infty}, R_1, R_2, C_1, C_2, \alpha_1, \alpha_2$) impedance parameters for the single and double dispersions, respectively. Early methods extracted the parameters graphically from an impedance plot relating the imaginary impedance, Z'', to the real impedance, Z'. However, with the rise of computers and very powerful numerical fitting software the majority of parameters are now estimated using non-linear least squares routines fitting experimental data to the desired model. Parameters are selected such that the least squares error between the experimental data and estimated response are minimized. While these fitting processes were initially applied to impedance data, research has been expanded to extract the parameters without requiring direct measurement of the impedance. Instead, parameters are extracted only from the real part of the impedance (Z') (Ward et al., 2006; Ayllon et al., 2009), the imaginary (Z''), or the modulus (Ayllon et al., 2009; Buendia et al., 2011, 2012; Freeborn et al., 2012a) components of the impedance, the conductance component of the admittance (Seoane et al., 2010) and even from time domain step response datasets (Freeborn et al., 2012b). Methods without requiring fitting routines have also been investigated to extract the parameters from the magnitude response (Elwakil and Maundy, 2010; Maundy and Elwakil, 2012) and the time domain response to a triangle-wave current input (Elwakil and Maundy, 2011). A significant motivation in the research of alternative methods for extracting the impedance parameters is to reduce the amount of hardware and cost of instruments for these measurements (Buendia et al., 2011). Traditionally, to collect the impedance data requires an impedance analyzer which is expensive and not portable, though portable hardware to accomplish this same task has been developed (Tiitta and Olkkonen, 2002; Solmaz et al., 2009; Lin et al., 2012; Seoane et al., 2008) with wearable instruments presented in (Ferreira et al., 2013) to monitor patients in real-time. However, these instruments use direct measurements of the impedance. By implementing indirect measurement techniques there is the potential to further decrease the cost of instruments by reducing the amount of required hardware.

This work applies a non-linear least squares fitting (NLSF) to extract the single and double-dispersion Cole impedance parameters

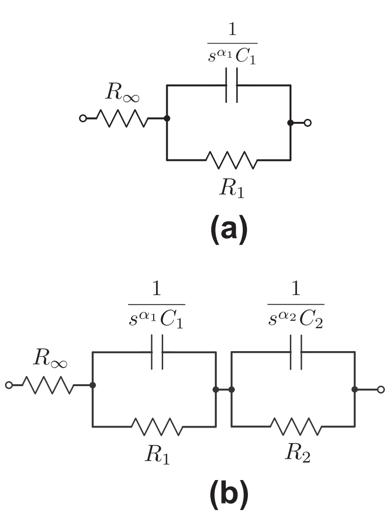

Fig. 1. Theoretical (a) single and (b) double dispersion Cole impedance models.