Michał WŁADZIŃSKI, Tadeusz PAŁKO

Warsaw University of Technology Institute of Metrology and Biomedical Engineering Department of Mechatronics

Impedance spectroscopy of tissue with extortion in a constant limited frequency band

Abstract. *This paper presents new approach to impedance spectroscopy measurements based on Fast Fourier Transform in biological application. The proposed solution uses a current excitation, which is continuous in a finite frequency range. The electrical response of tissue is measured using proposed circuit by two separate digital-to-analog converters. The impedance spectrum and the phase shift are computed by differentiation of complex spectrum obtained from FFT algorithm. The proposed method was simulated using state space representation and the results were presented*

Streszczenie. *Artykuł przedstawia nową metodę wyznaczania spektrum impedancji opartą o dyskretną transformatę Fouriera. W proponowanym rozwiązaniu zastosowano wymuszenie prądowe, którego widmo jest ciągłe w skończonym przedziale częstotliwości. Do pomiaru odpowiedzi elektrycznej tkanki został zaproponowany układ pomiarowy oparty na dwóch równoległych przetworniki analogowo-cyfrowe. Wyznaczanie spektrum impedancji oraz przesunięcia fazowego obliczane jest na podstawie różnic między widmami uzyskanymi z algorytmu FFT. Proponowana metoda została zasymulowana z zastosowaniem równań stanu, wyniki zostały umieszczone w opracowaniu. (**Spektrometria impedancyjna tkanek z zastosowaniem wymuszenia ciągłego w ograniczonym przedziale częstotliwości**)*

Keywords: Impedance spectroscopy, phase shift, state space representation.
Słowa kluczowe: Spektrometria impedancyjna, przesunięcie fazowe, równania stanu.

Introduction

All living organisms contain fluids mainly composed of electrolytes. In addition to fluids in the tissues are elements of structure which represent electrical barrier, such as bones, the collagens, proteins forming membranes of cells etc. The result is that the living tissues exhibit properties of a complex volume conductor [3,4]. In order to characterize the electrical properties of tissue, impedance measurement is performed for a specified frequency. The electrical impedance is a quantity dependent on the measured frequency, so for a full description of the properties of an object it has to be determined in a range of frequencies.

This paper presents a method for determining the impedance spectrum applied to the measurements of the impedance of tissues.

Calculating the impedance spectrum by measuring the amplitudes and the phase shift between current and voltage.

The most popular method of computing the impedance spectrum is based on measuring the impedance of the object as a function of frequency. Full range of sepectrum is computed by sweeping through a range of frequencies of current extortions.

The devices for impedance measurments are constructed with two separate circuits: the current source, which allows to change frequency and amplitude of extortions, and two high impedance differential amplifiers used to measure voltage and current in the measuring circuit (Fig.1).

In the measuring circuit the application electrodes are separated from receiver electrodes to eliminate influence of the electrode-tissue potencial.

The extortion generator provides sinusoidal current wave with stable amplitude and frequency, which is used to enforce current flow through the tissue. Current creates a differential voltage, which is measured by electrodes. Actual value of this current is measured on a serial resistor with fixed value using Ohm's law (eq. 1).

$$i(t) = \frac{u_R(t)}{R} \quad (1)$$

where: $i(t)$ - actual current value, $u_R(t)$ - actual voltage value at resistance R, R - resistance, t - time.

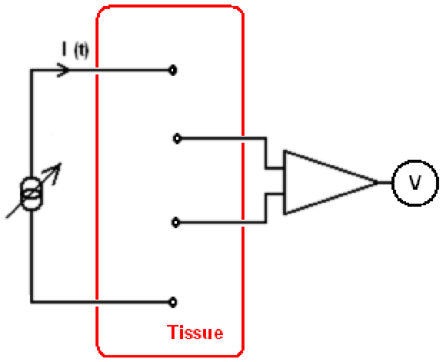

Fig.1. Impedance measurement system with tetrapolar connection of the extortion and measuring circuits

To determine the full impedance spectrum it is necessary to calculate two parameters: the impedance module and phase shift. Module impedance is calculated by using the current and voltage amplitudes (equ. 2) measured in the circuit. The current in this circuit is calculated using the Ohm's law, therefore the calculation of the impedance module could be simplified to the relation of two voltages.

$$M_Z(\omega) = \frac{(u_Z(\omega,t))}{(i(\omega,t))} = R \cdot \frac{(u_Z(\omega,t))}{(u_R(\omega,t))} \quad (2)$$

where: $M_Z(\omega)$- modulus of impedance Z, $U_Z(\omega,t)$ - voltage at measured impedance Z, $i(\omega,t)$ - current measured in the circuit, R - resistance, $U_R(\omega,t)$ - voltage at resistor R, ω - angular frequency, t - time.

The impedance phase shift calculation is based on the time measurement, where a delay between voltage and current waves in relation to the whole period is identified (eq. 3).

In hardware solutions the amplitudes of both waves are normalized to the same level.

$$\phi(\omega) = 2\pi \cdot \frac{t}{T_\omega} \quad (2)$$

where: $\phi(\omega)$ - phase shift, t - delay between current and voltage wave, T_ω - period.

The final result is the impedance for a specified frequency given as a complex number (eq 4).

$$(4)\qquad Z(f) = M_Z(f) \cdot e^{i \cdot \phi(f)}$$

where: $Z(f)$ - the impedance for a specified frequency, $M_Z(f)$ - module of impedance, $\phi(f)$ - phase shift.

Impedance spectrum is determined by completing a set of impedance measurements, calculated for specific frequencies

Calculating the impedance spectrum by using multi-sine-signal extortion.

The "multi-sine-signal" technique is based on the same measurement circuit as the previous one but with a different extortion signal, which contains many sine waves.

The extortion signal is synthesised in a digital form as described by equation (5) and then converted to a analog signal.

$$(5)\qquad x(nT) = \sum_{j=-(N-1)/2}^{(N-1)/2} A_j e^{\left[2\cdot\pi\left(f_c + j\cdot\Delta f\right)\cdot\left(nT\right) + \Theta_j\right]}$$

where: $x(nT)$ – an instantaneous value of X; A_j – amplitude of "j" component; Θ_j – phase of "j" component; f_c – main frequency; Δf – the difference between the main frequency and the first harmonic.

The response is amplified and converted to digital form, where each sine wave is separated by digital filters. The result of filtration is compared to the extortion signal and from their difference the impedance spectrum is calculated.

Calculation of the impedance spectrum using a with extortion with a constant limited frequency band.

The solution, which is proposed in this paper, is based on Fast Fourier Transformation. Accuracy of measurements is the reason for creating a special acquisition system. Main assumption for this new system is that both values - current and voltage must be converted to a digital form at the same point in time and recorded in a memory. A block diagram is presented in the figure 2.

The extortion circuit has two parts (fig. 2): a generator and voltage controled current source. The generator contains a large memory where a timing diagram is storedand is triggered externally. The generator converts digital data to a analog signal.

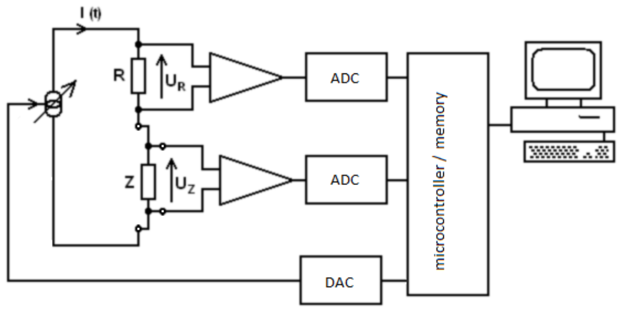

Fig. 2. The block diagram of measurement and acquisition system

In presented method the timing diagram is a sinc function, which has a constant Fourier transform, a *rect(f)* function. The *rect(f)* has a constant value in a limited band and it is a function of the sinc function period and can be modified.

The extortion and the measured response in a time domain are transformed using a discrete Fourier transform and as a result we receive the frequency domain representation (eq. 6)

$$(6)\; F(\omega_k) = \sum_{i=0}^{N-1} f(t_i) \cdot e^{-i\frac{2\cdot\pi\cdot\omega_k\cdot t_i}{N}} \qquad for\; k = 0,1,2,,N$$

where: $F(\omega_k)$ - discrete Fourier transform, $f(t_i)$ - samples, ω - angular frequency, t - time.

As a result of discrete Fourier transform we receive a sequence of complex numbers, representingconsecutive values of each frequency contained in the spectrum.

After initial processing impedance spectrum is computed in two steps: calculation of impedance modulus and phase shift.

The modulus of impedance for one frequency is calculated as a quotient of modules of complex values of the voltage and the current. (eq. 7).

$$(7)\qquad M_z(\omega_k) = \frac{U_Z(\omega_k)}{I(\omega_k)} = R\frac{U_Z(\omega_k)}{U_R(\omega_k)}$$

where: $M_Z(\omega_k)$ - impedance modulus, $U_Z(\omega_k)$ - Fourier transform of voltage at the impedance Z, $M_R(\omega_k)$ - Fourier transform of voltage at the resistance R, $I(\omega_k)$ - Fourier transform of current waveform , R - resistance , ω_k - angular frequency,

When the measurement of the current in the circuit is carried out using a serial resistor, then its resistance should have a value comparative to the impedance modulus.

The phase shift of impedance for one harmonic of spectrum is calculated as an angle between voltage and current vectors in the complex plane in polar coordinate system (fig. 3). The angle must be calculated in the same direction for eg. clockwise to prevent error of mixed positive and negative values.

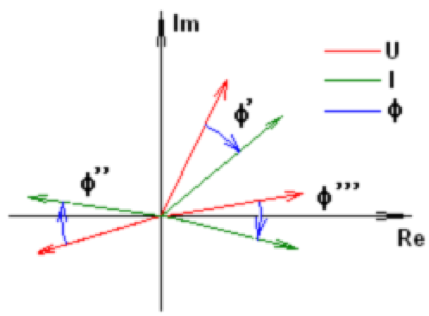

Fig. 3: Method of determining the angle between two complex numbers to caclulate phase shift.

The impedance spectrum is determinated completely when all transformed values have been calculated. The result can be described by the equation (eq. 8).

$$(8)\qquad Z(\omega_k) = M_Z(\omega_k) \cdot e^{2\pi\cdot i\cdot\omega_k} \quad for\; k = 1,2,..,N$$

where: $Z(\omega_k)$ - complex impedance, $M_Z(\omega_k)$ - modulus of impedance, $\phi(\omega_k)$ - phase shift, ω_k - angular frequency.

Numerical simulation of the proposed method in Matlab environment.

Proposed method was tested by means of a simulation carried out in Matlab (Mathworks), using appropriate models of tissue. For the simulation a simple electrical model of tissue was chosen. It consisted of one capacitor and two resistors (red rectangle fig. 4). The model of the full circuit has been described by a state space representation with each element described by a first-order differential equations. The extortion, which was *sinc* function, has been chosen to cover band between 0 and 100 kHz.

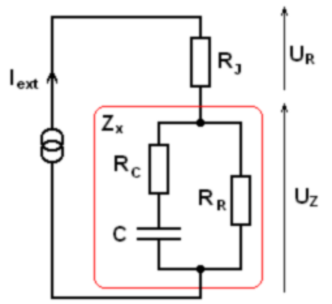

Fig. 4. Circuit modeled for the simulation.

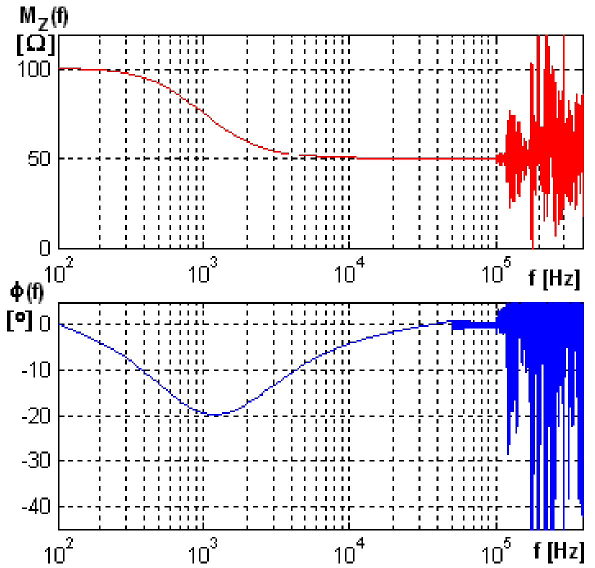

Fig. 5. Simulation results obtained for the Fourier-based method for impedance spectrum calculation..

In simulated model the circuit parameters were: R_R = 100Ω; R_C = 100Ω; C = 3,3µF. The sample rate had been fixed on 10MPS and the window function was rectangle with duration of 0.01s.

The simulation of the state wascomputed and the results were transformed to frequency domain by FFT algorithm. Both frequency representations U_R i U_Z were used to determine the impedance spectrum of the simulated circuit. The results are presented in a bode plot in figure 5.

After the simulation, the measurements were carried out on a physical model with electrical characteristics similiar to those of the living tissue. A sinc(x) function generator with programmable waveforms and voltage-controlled current source was used. The current and voltage were measured by differential amplifiers and recorded on a oscilloscope. Unfortunately, the oscilloscope used did not provide simultaneous measurements of both channels. This resulted in significant errors in determined phase characteristics.

Summary

The new method, which was presented in this paper, is much faster than others. the calculation full impedance spectrum with required accuracy in a frequency domain depend on sample rate and window of measuring duration. The special measurement system is required to eliminate error.

The method can be easy apply to impedance spectroscopy of tissue in a living organism, especially when the movement caused by changing blood pressure

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***Authors**: mgr inż. Michał Władziński, Politechnika Warszawska, Instytut Metrologii i Inżynierii Biomedycznej, ul św. A. Boboli 8, 02-525 Warszawa E-mali: m.wladzinski@mchtr.pw.edu.pl; prof. dr hab. Inż. Tadeusz Pałko, Politechnika Warszawska, Instytut Metrologii i Inżynierii Biomedycznej, ul św. A. Boboli 8, 02-525 Warszawa E-mali: T.Palko@mchtr.pw.edu.pl;*