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Using of Chirp Excitation for Bioimpedance Estimation: Theoretical Aspects and Modeling

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ABSTRACT: In this paper, theoretical considerations and simulation results of a method for quick estimation of the bioimpedance (BI) vector over a wide range of excitation frequencies are discussed. This method uses a chirp signal with linearly modulated frequency for excitation. The response signal is processed using cross-correlation techniques together with following fast Fourier transform (FFT). As the result, the complex spectrum of the response signal is attained in the range of frequency, determined by the spread of chirp pulse. This spectrum characterizes the frequency response of the impedance under study.

1 Introduction

Using frequency sweeps, often together with pulse compression and Fourier analysis, has been implemented in various areas of engineering as radar and sonar techniques, acoustic and ultrasonic, optical and seismological studies, etc. [1-5].

In this paper, a similar method is proposed for estimation of the frequency response of electrical bioimpedance (the impedance spectrum).

An advantage of the method of fast frequency sweep is that the characteristics of biological object in a wideband frequency range can be obtained during a very short measurement cycle, which nearly eliminates the impact of low-frequency biological processes to the result of measurement.

The pulse compression by means of cross-correlation yields a better noise immunity for the measurement system, also. Spectral changes monitored at sequent time intervals can be a good base for interpreting processes in the biological objects.

2 Measuring principles

A sine-wave excitation pulse with linearly modulated frequency (FM), called chirp, can be expressed as

$$V_{\mathrm{ch}}(t)=\sin\left(2\pi\left(f_1 t+(f_2-f_1)t^2/2T_{\mathrm{ch}}\right)\right) \qquad (1)$$

where f_1 and f_2 are the initial an final instant frequencies of sweep, respectively, and T_{ch} is the duration of the chirp pulse.

Usually, the use of some windowing function $w(t)$ is desirable to reduce the impact of Gibbs effect and to smooth the measurement results. When windowing, the actual excitation signal (stimulus) is $V_{\mathrm{exc}}(t)=w(t)\cdot V_{\mathrm{ch}}(t)$. For amplitude tapering of chirp pulses, a Tukey-style windowing is often preferred [1, 2, 4].

In particular experiments, we used a modified Tukey window with sine-squared tapering [4]. In this case, the amplitude suppression occurs during a certain tapering time t_{a} according to the rule (2). For $t_{\mathrm{a}}\le t\le T_{\mathrm{ch}}-t_{\mathrm{a}}$ the amplitude of chirp remains unchangeable. The initial and final amplitudes are denoted in (2) as a_0:

$$w(t)=\begin{cases} a_0+(1-a_0)\sin^2\left(\dfrac{\pi t}{2t_{\mathrm{a}}}\right); & t<t_{\mathrm{a}} \\ a_0+(1-a_0)\sin^2\left(\dfrac{\pi t-(T_{\mathrm{ch}}-2t_{\mathrm{a}})}{2t_{\mathrm{a}}}\right); & t>T_{\mathrm{ch}}-t_{\mathrm{a}} \end{cases} \qquad (2)$$

The waveform of the windowed chirp stimulus V_{exc} is shown in Fig. 1.

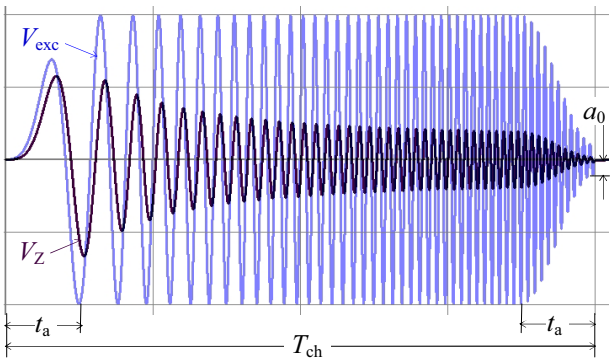

Fig. 1. An example of the chirp excitation and of the response.

The excitation current $I_{\mathrm{exc}}(t)$ from a voltage-to-current converter V/I through a bioimpedance under study $\boldsymbol{Z}=|Z|\exp(\mathrm{j}\Phi_Z)$ causes a response voltage $V_Z(t)$ The response is attenuated and shifted in phase in relation to the excitation at every instant of time differently, depending on the instant frequency of the chirp (Fig. 1).

For a good approximation of the electrical bio-impedance Z (or EBI) of a biological object we used the 5-element electrical equivalent (see Fig. 2a) [6], Laplace transform of which can be expressed as

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$$Z = \frac{R_0(1+sC_1R_1)(1+sC_2R_2)}{sC_2(1+sC_1(R_0+R_1))\left(\frac{1+sC_2R_2}{sC_2}+\frac{R_0(1+sC_1R_1)}{1+sC_1(R_0+R_1)}\right)} \quad (3)$$

At actual physical values of extracellular resistance R_0 and intracellular parameters R_1, C_1, R_2 and C_2 the adequate Bode diagram has two real poles f_{p1}, f_{p2}, and two zeros f_{z1}, f_{z2}, respectively (Fig. 2b).

For the proposed solution, the response signal is cross-correlated with the prior excitation V_{exc} and this process can be expressed as

$$r_{xy}(\tau) = \mathrm{Corr}(V_Z(t), V_{exc}(t)) = \overline{V_Z(t)V_{exc}(t+\tau)} \quad (4)$$

where τ is a variable delay (lag).

Using broadband chirp excitation, the waveform of correlation function $r_{xy}(\tau)$ is similar to the sin$x$/x type sinc-function affected by the nature of V_Z and is strongly compressed close to $\tau = 0$. On the other side, in accordance with the cross-correlation theorem (generalized Wiener-Khinchin theorem), the correlation function is equivalent to the inverse Fourier transform of the cross-power spectrum density, being the measure of coherence between V_Z and V_{exc} [7]. Thus, in our case, the FFT-processing of the correlator output yields broadband spectrum of the biological object under study.

3 Modeling of the system

To verify the theoretical conceptions a special PC-model was developed, core structure of which is described in Fig. 2a.

In modeling, it is obligatory that the selected sampling rate f_s meets the Nyqvist criterion over the whole frequency range, i.e., the condition $f_s \geq 2f_2$ must be fulfilled. The sampling rate determines the total number of samples N during a chirp pulse as $N = T_{ch}f_s$, which is the base for averaging of sum $\sum_n V_Z[n]V_{exc}[n+\tau]$ for every τ value ($n = 0 \ldots N-1$).

If the uniform delay step is $\Delta\tau$, then for a delay interval (observation time) $t_{obs} = \tau_{max} - \tau_{min}$ ($\tau_{min} \leq \tau \leq \tau_{max}$) the number of necessary computing cycles is $M+1$ with $M = t_{obs}/\Delta\tau$. As a result, we acquire an array of correlation values $r_{xy}[m]$ with $m = 0 \ldots M$:

$$r_{xy}[m] = \frac{1}{N}\sum_{n=0}^{N-1} V_Z[n] \cdot V_{exc}[n-\tau_m] \quad (5)$$

Supposing that the selected $\Delta\tau$ and τ_{min} are integer multiples of the sampling interval $1/f_s$, the m-th delay expresses as $\tau_m = f_s(\tau_{min}+m\Delta\tau)$.

From (5) the correlation coefficient C_{xy} ($|C_{xy}| \leq 1$) can be calculated as $C_{xy} = r_{xy}/D$, using normalizing factor

$$D = \frac{1}{N}\sqrt{\sum_{n=0}^{N-1} V_Z{}^2[n] \cdot \sum_{n=0}^{N-1} V_{exc}{}^2[n]} \quad (6)$$

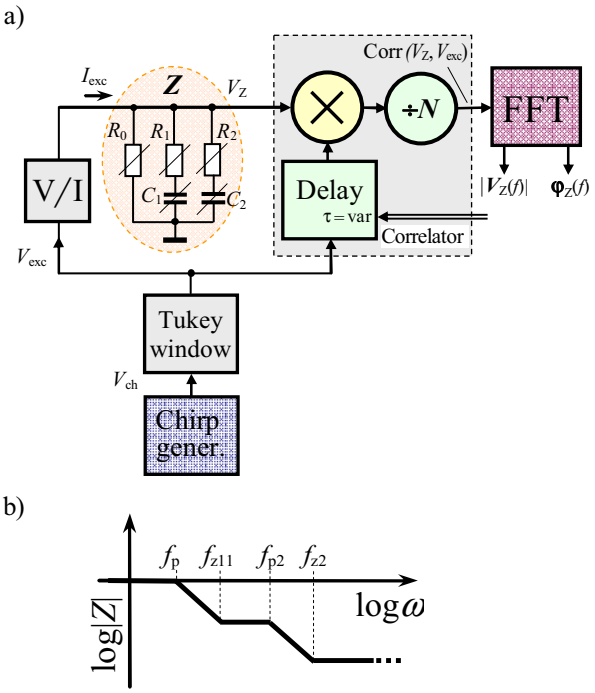

Fig. 2. Model of measurement system (a); and Bode diagram of the EBI (b).

The array r_{xy} of length $M+1$ represents the input function for the Fast Fourier Transform (FFT) block. The FFT procedure returns the real and imaginary transfer functions Re($V_Z(f)$) and Im($V_Z(f)$), while in accordance with the uncertainty principle [7], the frequency resolution becomes $\Delta f = 1/t_{obs}$ over the frequency range $f = 0 \ldots 1/(2\Delta\tau)$. The following calculation of module $|Z(f)|$ and phase $\Phi_Z(f)$ of the EBI is elementary.

In principle, the frequency response of the biological object under test can be obtained using direct FFT processing of the signal array V_Z of length N, which depends on the sampling of excitation signal [8]. On the contrary, the number M of correlation values is not dependent on the f_s, and at high sampling rate usually $N >> M$. For that reason, the proposed method can be more effective and fast at the FFT calculus, if compared to direct processing of the V_Z.

To obtain the same results, the direct processing may require splitting of frequency range and several cycles of calculus are needed. Besides, as the cross-correlation function r_{xy} includes both the information about amplitude and phase shift between V_{exc} and V_Z, then only a single FFT cycle is necessary to acquire this information, unlike the direct V_Z processing, where the basis of phase shift is absent.

The last fact is especially important in embedded applications, for example in implantable and wearable medical devices and micro/nano scale bioprocessor and laboratories like bioMEMS, lab-on-chip, and bioprocessor-on-chip [5].

4 Simulation results

Next, some typical examples of simulation results are shown. In all cases, the linear chirp from $f = 1$ Hz to 100 kHz with duration $T_{ch} = 10$ ms and unity amplitude was implemented. The windowing parameters $a_0 = 0.1$ and $t_a = T_{ch}/8$ were used. The sampling rate $f_s = 1 \cdot 10^6$ to $5 \cdot 10^6$ samples/s was applied in experiments.

Fig. 3 illustrates chirp compression by the correlator in stretched time scale. The normalized autocorrelation $C_{xx}(\tau)$ is equivalent to the cross-correlation over the unit (etalon) impedance $\boldsymbol{Z_0}$ with $|Z_0| = 1$ and $\Phi_Z = 0$. The coefficient $C_{xy}(\tau)$ qualifies similarity between excitation and response at $Z = Z_1$ (see Table 1). The respective curves of amplitude frequency response from the FFT are shown in Fig. 4. At the same time, the effect of windowing can be watched in Fig. 4.

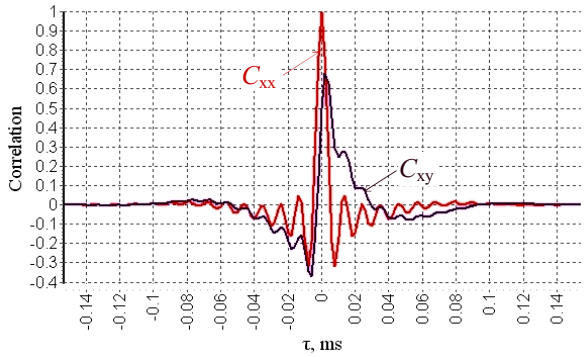

Fig. 3. Normalized autocorrelation (C_{xx}) of the excitation and cross-correlation (C_{xy}) between excitation and response for the model $Z = Z_1$ at time interval $\tau = -1.5 \ldots +1.5$ ms, determined with $\Delta\tau = 0.002$ ms.

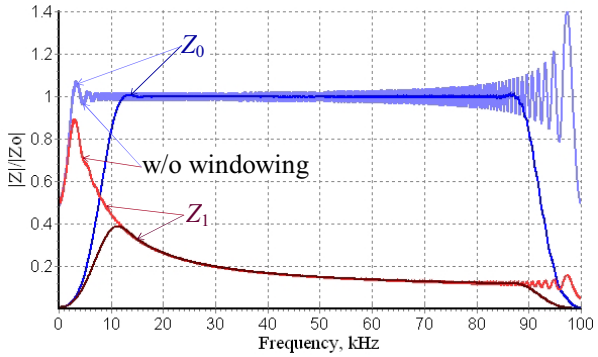

Fig. 4. Frequency response $|V_Z(f)|$ for the etalon impedance Z_0 and for the EBI equivalent Z_1 with and without (w/o) windowing.

Figures 5 and 6 enable to compare the changes in spectrum caused by variance of the EBI components in accordance with Table 1. For the simulations, which gave the results presented in Fig. 4 to Fig. 6, the delay step $\Delta\tau = 0.005$ ms was used.

Table 1. Parameters of the EBI equivalent at experiments.

Z	R_0	R_1	C_1	R_2	C_2	f_{p1}	f_{z1}	f_{p2}	f_{z2}
	Ω	Ω	nF	Ω	nF	kHz	kHz	kHz	kHz
Z_1	1000	200	20	100	10	4.8	39.8	82.2	159.2
Z_2	1000	200	40	100	10	2.8	19.9	70.6	159.2
Z_3	1000	200	10	100	10	7.4	79.6	107.0	159.2
Z_4	1000	200	20	100	20	3.7	39.8	53.5	79.6

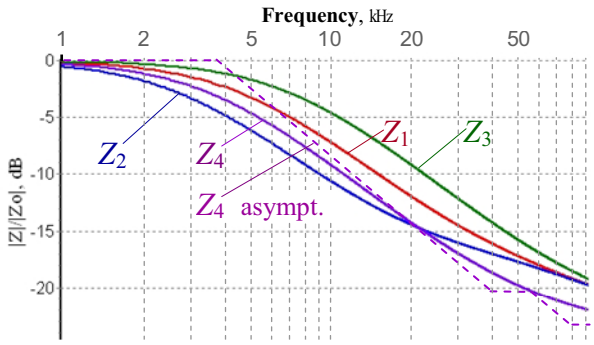

Fig. 5. Relative magnitudes of the bioimpedance (EBI) for different combinations of the parameters of equivalent circuit (Fig.1b) Z_1 to Z_4 according to Table 1, together with calculated asymptotic Bode diagram for Z_4.

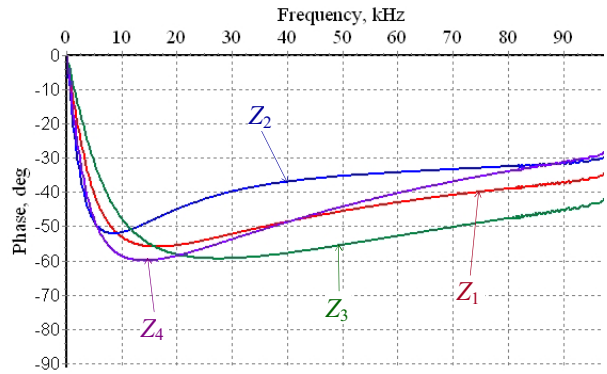

Fig. 6. Phase response for different equivalents of the EBI Z_1 to Z_4 (see Table 1).

It has to be noticed here, that for obtaining accurate results for the phase response $\varphi_Z(f)$ using of rather high sampling rate, e.g. $f_s \geq 10 \cdot f_2$ is recommendable.

Concurrently, namely the phase response enables to estimate the changes of the parameters of the EBI even more impressively than the amplitude response, as it can be seen from Fig. 6. Moreover, the phase information is a relative parameter depending only on the ratio of imaginary and real parts of the impedance, not on their absolute values, as the relative changes of bioimpedance express the dynamics of physiological processes in the living tissue.

5 Practical prospects

The modeling proved that the introduced method can ensure sufficiently good estimation of the EBI spectrum, especially at high sampling rate. However, generating of the perfect sine-wave chirp is quite complicated and power consuming in practical solutions. Keeping in view simplifying of practical implementation, some tests with excitation of rectangular waveform (signum-chirp) $V_{sch}(t)$=sign($V_{ch}(t)$) were accomplished. For better visualization, only the first quarter of a signum-chirp pulse and of the respective response V_Z(t) are shown in Fig. 7.

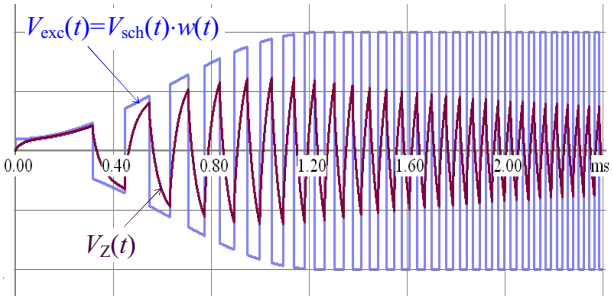

Fig. 7. Initial segment of the windowed linear signum-chirp and the respective response at $Z=Z_1$ (T_{ch}=10 ms, f=1 to 10^5 Hz).

In this case, one can speak about so-called sign cross-correlation between the excitation and response, which simplifies the calculations considerably. At the same time, using of signum-chirp can involve dissipation of results due to accompanying of higher harmonics - see Fig. 8.

To overcome this problem, a proper selection of correlation parameters is important, while rather shorter t_{obs} with more rough frequency resolution is appropriate. In Fig. 8, one can compare the phase responses evaluated at equal array length M, but at different frequency resolution (curves (b) and (c)). For comparison, the phase response at sine-wave chirp is shown as the curve (a).

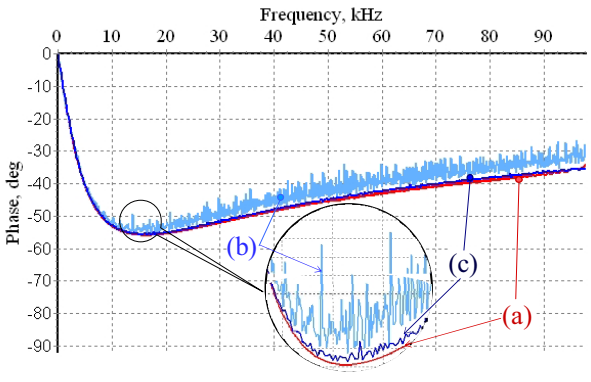

Fig. 8. Phase response for $Z=Z_1$ at different excitations: (a) sine-wave chirp; (b) signum-chirp at t_{obs}= 10 ms, $\Delta\tau$ =0.005 ms, and Δf =100 Hz; (c) signum-chirp at t_{obs}= 4 ms, $\Delta\tau$ =0.002 ms, and Δf =250 Hz.

6 Conclusions

These very promising results of simulation encourage us to continue with practical development of the perspective system for bioimpedance measurement.

In comparison with the direct using of the FFT procedure on the response signal, this method gives considerable economy in the necessary computing power, especially when utilizing high sampling rate for improving the precision of measurement.

The main advantage of the proposed method is quickness of estimation of complex spectrum of the impedance of a biological object in the wide range of frequencies. Accordingly, the method is implementable, e.g. in high throughput microfluidic laboratory-on-chip type devices for performing bioimpedance based joint time-frequency domain analysis of cells, cell cultures and droplets.

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