Improved extraction of information in bioimpedance measurements

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Abstract. A wideband bioimpedance measurement method is proposed, which can enhance the interpretation of measurement results due to the improved resolution of monitoring. On the other hand, the corresponding measurement system uses a binary chirp waveform for excitation signal, which simplifies the signal processing hardware and does not require sophisticated software. It is shown that the binary chirp excitation has some essential advantages compared to its counterpart – the maximum length sequence (MLS) excitation.

1. Introduction

Often, the theoretical study of passive electrical properties of a biological object (bioimpedance of the living tissue or cells) is substituted by the analysis of its electrical equivalent (EBI). The EBI represents a definite set of resistive and capacitive components, changes of which (dynamics) can be described by a frequency dependent vector $Z(j\omega) = |Z(\omega)|\exp(j\Phi_Z(\omega))$, where $\omega = 2\pi f$.

This vector characterizes the EBI and approximates the state and properties of the respective object under study. Mostly, the dynamic features of this vector appear within a frequency range from some kHz to several MHz ($\beta$-region) depending on changes in the structural properties of the biological object [1]. To obtain information about the object in a wide frequency range, it is appropriate to study the impedance $Z$ in frequency domain applying the Fourier Transform $\mathcal{F}(\cdot)$ to both – the output response voltage $V_z(t)$, and the excitation (stimulus) current $I_{exc}(t)$:

$$Z(j\omega) = \mathcal{F}(V_z(t))/\mathcal{F}(I_{exc}(t))$$

To maximize the information from the study, the bandwidth of the excitation should coincide with the frequency range changes of the object as much as possible. Different broadband signals, scalable in frequency (multisines, chirps, maximum length sequences (MLS)) have been in use for excitation [2]. In this work, we emphasize the advantages of chirp waveforms. The chirp excitation signal can be scaled easily as in frequency, as well in time domain. Besides, the chirps have almost flat or tunable amplitude spectrum over the whole generated range, so increasing the accuracy of measurement.

However, the generation of a perfect sine-wave chirp is complicated. To reduce the complexity of required software and hardware, a binary excitation should be preferred. A good choice is the binary chirp or pseudo-chirp [3], which can be a successful rival to the MLS excitation.

To improve the quality of monitoring in the frequency domain, we suggest a 2-channel measurement method and the corresponding system. It incorporates measurement and reference channels together with spectral analysis of both, the response signal from measurement channel and the reference signal from the other channel. Finally, analysis of the phase spectrum instead of the amplitude one is proposed [4, 5].
2. Binary chirp vs. MLS
Chirp-type signals can be classified by the rule of changing their instantaneous frequency. The basic class covers so-called power-law chirs, the frequency of which changes by a power function.

A sine-wave power-law chirp of the power of \( n \) (the simplest linear chirp has \( n=1 \)) and with amplitude \( A \) can be described mathematically as

\[
V_{\text{ch}}(t) = A\sin\left(2\pi f_0 t + \beta t^{n+1} \right),
\]

in which \( \beta = \frac{B_{\text{exc}}}{T_{\text{ch}}} \) characterizes the rate of frequency variation, \( B_{\text{exc}} = f_{\text{fin}} - f_0 \) is the excitation bandwidth between the final \( f_{\text{fin}} \) and initial \( f_0 \) frequencies, and \( T_{\text{ch}} \) is the duration of chirp pulse.

A binary chirp with two values \( \pm A \), expressed mathematically as \( V_{\text{bin}}(t) = A \text{sign}\{V_{\text{ch}}(t)\} \), is illustrated in Figure 1a. For comparison, the Figure 1b depicts a fragment of a similar 11-stage MLS signal. In Figure 1c, the power spectral density (PSD) of a binary chirp and the corresponding 11-stage MLS with equal energies and the same duration \( T_{\text{ch}} = T_{\text{MLS}} = (2^{11}-1)/f_{\text{clk}} \approx 20.47 \text{ ms} \) are compared at the clock frequency \( f_{\text{clk}} = f_{\text{fin}} = 100 \text{ kHz} \). For the contrast, the PSD of a sine-wave chirp is shown, too.

![Figure 1.](image-url)

(a) Waveforms of sine-wave (V\text{ch}) and binary (V\text{bin}) chirs; (b) waveform of the 11-stage MLS signal; (c) power spectra of sine-wave and binary chirs, and the MLS with equal durations.

The envelope of the MLS spectrum is the sinc-function, which reduces to zero at \( f = kf_{\text{clk}} \) \((k = 1, 2, 3, \text{ etc.})\). It means that the main bandwidth \( B_{\text{exc}} = f_{\text{clk}} \) of MLS is not entirely usable in measurements. On the contrary, the PSD of chirs covers the whole generated bandwidth \( B_{\text{exc}} \). Thereby, the average PSD of the binary chirp exceeds the PSD of the respective sinusoidal chirp \((4/\pi^2)\) times and is equal to the PSD of MLS at the frequency of \( f_{\text{fin}}/2 \), approximately.

The drawback of binary chirp excitation is the intensively fluctuating amplitude spectrum. Fortunately, it is recouped by several benefits:

- The generation of binary chirs is simple, only a bit more complicated as the MLS. It can be done by following the current phase \( \theta(t) = \int \omega(t) dt \) and counting the samples. If \( f_0 = 0 \) and \( n = 1 \), then the current phase in (2) expresses as \( \theta(t) = \pi \beta t^2 \). The polarity must alternate at every \( \theta(t) = k\pi \) \((k = 0, 1, 2, \ldots)\), i.e., at every integer value of \( \beta t^2 \). Consequently, the polarity must be changed at every \( k_{\text{th}} \) sample, where \( k_{\text{th}} = \text{round}\left(f_{\text{sam}}(k\beta)^{1/2}\right) \) and \( f_{\text{sam}} \) is the sampling frequency.
- Alike the MLS, the crest factor of binary chirs is 1, which means that the utmost power or energy is available. It accompanies with sufficiently high energy efficiency \( \delta_{\text{ch}} \) (the percentage of generated energy within the excitation bandwidth \( B_{\text{exc}} \)), which is theoretically \( \delta_{\text{ch}} \approx 0.853 \) [6].

3. Structure of the measurement system
The fluctuating spectrum complicates interpreting of the measurement results especially in the case, where the amplitude spectrum is the only source of information. Therefore, it is reasonable to catch the spectral information from the phase spectrum, which is more insensitive to the fluctuations within the bandwidth \( B_{\text{exc}} \). Moreover, the phase spectrum does not depend on the signal levels. However, to get the phase spectrum we need a reference to evaluate the phase shift.
Furthermore, often the actual value of the impedance $Z$ is not of great importance. We are more interested in observing $Z$ variations caused by the changes and events inside the object. For that reason, we consider the two-channel measurement system, wherein one of the channels includes predefined reference impedance $Z_{\text{ref}}$, which is approximately equal to the $Z$ and is composed using a priori information about it. Such a structure behaves as the matched filtering, showing zero output of the phase spectrum if $Z=Z_{\text{ref}}$, and enabling to detect tiny deviations in the phase spectrum. Thereby, in the reference channel we can use an equivalent analog RC-circuit as well as a set of numerical values (a digital model) obtained from a previously stored response $V_z$. This task can be accomplished by a simple structure with two FFT-blocks for transforming the response and reference signals $V_z$ and $V_{\text{ref}}$ separately (Figure 2a). The complex numbers from the both of blocks are divided for obtaining the spectra of the relative amplitudes $|Z(f)|/|Z_{\text{ref}}(f)|$ and phase differences $\Delta \Phi(f)=\Phi_z(f)-\Phi_{\text{ref}}(f)$.

Another solution in Figure 2b implements the cross-correlation procedure with the signals $V_z$ and $V_{\text{ref}}$. The product $r_{zx}$ of the cross-correlation function (CCF) includes the information about the amplitude and phase of the both signals, and only a single FFT-block is used for producing a cross-power spectrum $|P_{zx}(f)|$ and the spectrum of phase differences $\Delta \Phi_{zx}(f)$. This method is somewhat slower due to the calculations of CCF, but enables to obtain some additional information on declinations of $Z$ from $Z_{\text{ref}}$ throughout the CCF (see Figure 3) and has a better noise immunity.

![Figure 2](image_url)

**Figure 2.** The structures of measurement system: (a) with two separated FFT channels; (b) with cross-correlation calculus; (c) general model of the bioimpedance used in simulations and calculations.

### 4. Simulation results

The following simulation results are obtained by the model developed in accordance with the circuit in Figure 2b. A simple 3-element RC-circuit in Figure 2c ($R_0=1 \, k\Omega$, $R_1=200 \, \Omega$ and $C_1=20 \, nF$) represents the reference impedance $Z_{\text{ref}}$, which is approximating of an “unknown” object $Z$ as well as.

![Figure 3](image_url)

**Figure 3.** (a) Normalized voltage signals; (b) normalized cross-correlation functions: $Z_{\text{ref}}=1$ and $Z_{\text{ref}}=Z$.

Figure 3a shows initial cycles of the binary chirp $V_{\text{exc}}$ ($f_0=0$, $f_{\text{fin}}=100 \, kHz$, $T_{\text{ch}}=10 \, ms$) and the respective response $V_z$ to this excitation. Figure 3b shows the CCF in two extreme cases: $Z=Z_{\text{ref}}$ and $Z_{\text{ref}}=1$.

Figure 4a demonstrates the main result of the proposed measurement method – the possibility to distinguish very small variations of components of $Z$ through the spectra $\Delta \Phi_{\text{dif}}(f)$. The concurrent
simulations proved that the MLS excitation cannot ensure such clearness of the phase spectrum as the binary chirp excitation does – see Figure 4b.

![Figure 4](image)

**Figure 4.** Spectra of phase declinations at the +1% increments of Z components in the case of following excitations: (a) binary chirp; (b) binary chirp and pseudo-random MLS at the changing C₁.

5. Conclusion

The proposed method conjoins different means to improve the quality of bioimpedance measurements.

First, the use of binary waveform chirps for excitation simplifies the required hardware and software essentially in the practical developments, but assures the measurement in a wide frequency band at the same time. In addition, simulations pointed out some advantages as independent scaling in both time and frequency domain when compared with another popular binary signal – maximum length sequence (MLS).

Second, by focusing on the phase spectrum, the binary chirp waveform enables to avoid the disturbing impact caused by the higher harmonic components inherent to all the binary excitations.

Third, the using of two-channel measurement system with the reference impedance in one of two channels (designed on the basis of *a priori* knowledge), increases the accuracy of measurement substantially and permits to detect tiny changes in the structure and/or parameters of the unknown bioimpedance to be measured.

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