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Binary Signals in Impedance Spectroscopy

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***Abstract*– Using of binary waveforms in the fast impedance spectroscopy of biological objects is discussed in the paper. There is shown that the energy of binary waveforms can be concentrated onto selected separate frequencies. We can optimize the binary excitation waveform depending on the shape of frequency response of the impedance under study to maximize the levels of signal components with certain selected frequencies. As a result, we are able to receive maximal amount of information about the properties and behavior of the impedance to be studied. We have designed and prototyped the impedance spectroscopy device operating in the frequency range from 100 mHz to 500 kHz to cover α- and β-regions of the bio-impedance spectrum of time-varying subjects as, for example, fast moving cells in micro-fluidic devices, beating heart and breathing lungs or the whole cardiovascular system.**

I. Introduction

Electrical bio-impedance spectra are used to characterize the structure of living tissues and cell cultures [1]. Also single cells can be detected and their behavior characterized even if the parameters of which are changing fast, e.g. when the cells and cell droplets move through the lab-on-chip device [2] or nerve cells are fired. Only a millisecond can be allowed to avoid significant dynamic errors in this case.

Bio-impedance spectra have a tendency to decrease at higher frequencies. It means that the intensity of response signals picked up from the subject also decreases with frequency [1]. The decrease is relatively small in blood spectroscopy, but can be intensive (nearly inverse proportional to the frequency) in the case of single cells or dry skin spectroscopy. If the frequency range of interest is significantly wide, the picked up response from the subject under study decreases tens and hundreds of times with increasing frequency. Along with signal degradation, also the signal-to-noise ratio goes down. As a result, an accurate digital processing of the response signal requires 18- to 20-bit digitizing [3]. Pre-emphasizing the selected higher frequency components in the excitation signal spectrum enables to improve the signal-to-noise ratio and lessen the resolution requirements to about 12-bit level, which makes the cost effective bio-impedance spectroscopy available.

A simplified architecture of the bio-impedance spectroscopy system is presented in Fig. 1. A generator of binary current excitation I_{exc} has inputs for timing and duration control (from t_1 to t_k) and for frequency range setting (from f_1 to f_n). The binary signal from this generator is used as an input excitation for the complex impedance $\dot{Z}$ under study, as well as a reference signal for the phase sensitive processing of a response voltage V_z fm the impedance $\dot{Z}$. Discrete or fast Fourier transforms (DFT or FFT) are used for obtaining the amplitude and phase spectra $|\dot{Z}(f)|$ and $\Phi(f)$ of the impedance $\dot{Z}$.

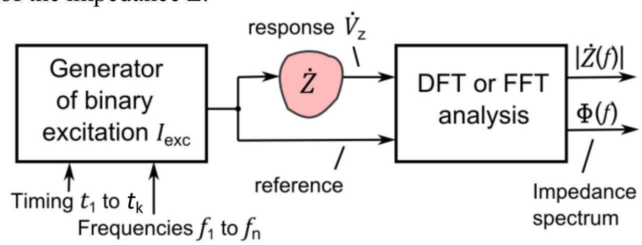

Figure 1. A simplified architecture of the spectroscopy system designed for measurement and analysis of complex bio-impedance $\dot{Z}$.

II. Simple Binary Excitations

Classically the single and multiple (multi-frequency) sine waves or sine wave based chirps are used in impedance measurements [4-6]. However, there are found out last time that some discrete binary waveforms can not only be generated in simple way, but also the amount of useful excitation energy in these exceeds the energy of comparable sine wave based signals [5-9]. One simplest practically used binary excitation is a short single pulse (Fig. 2a), which has a broad band continuous spectrum (Fig. 2b) with only slightly declining RMS spectral density up to the frequency (1/2T), but the spectral density remains too low for the most of applications. Therefore the low signal-to-noise ratio creates serious problems.

The other known waveform is a simple rectangular signal with binary (+1 and -1) levels, see Fig. 3a. Unfortunately the sparse spectrum of this waveform contains only odd harmonics (1^{st}, 3^{rd}, 5^{th}, 7^{th}), which are declining fast with frequency by 1/f rule (Fig. 3b). Such the simple waveform can be used, therefore, only in some special cases. The waveforms in Fig. 2 to Fig. 8 are built up using 1000 sample points within their normalized period T_p.

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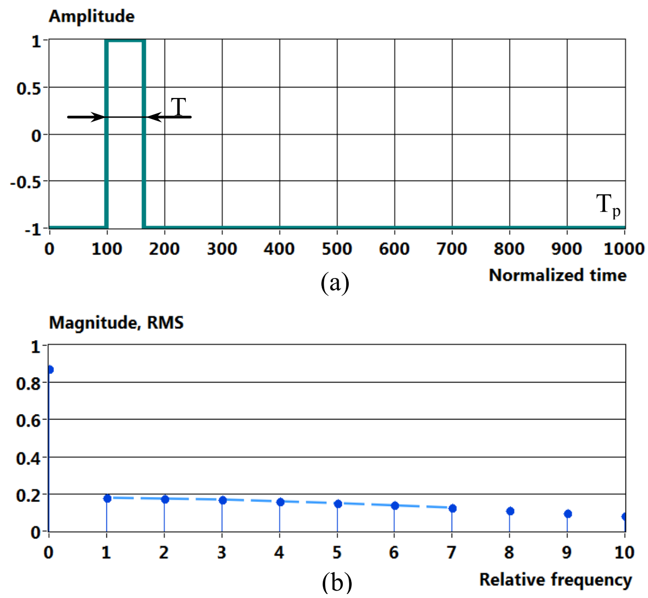

Figure 2. Waveform (a) and RMS spectrum (b) of a pulse with relative duration T = (64/1000) T_p; the spectrum has a DC component (f =0) and a slightly declining low level spectral density at the frequencies of interest.

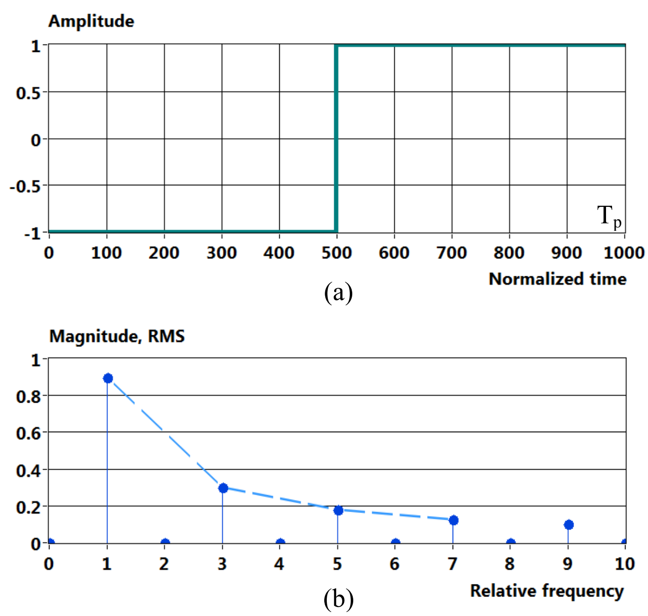

Figure 3. Waveform (a) and RMS spectrum (b) of a rectangular waveform; the frequency bins from 1 to 7 occupy 95 % of the total signal energy.

III. Synthesized Binary Signals

Spectrally sparse multi-frequency binary waveforms (spectrally adjusted sequences – SAS) can be synthesized in several ways [5-9]. If the number of frequency components (bins of spectra) n is below 10 ($n=4$ in our examples), varying the durations of binary pulses can be used for finding the desired spectral shape. An edge manipulation method can be used for finding the edge locations or transition instances (time instant, where the signal level is switched from +1 level to –1 level and vice versa, see Fig. 4a). For example, a binary waveform is manipulated in such a way to obtain the spectral lines with equal amplitudes (Fig. 4b).

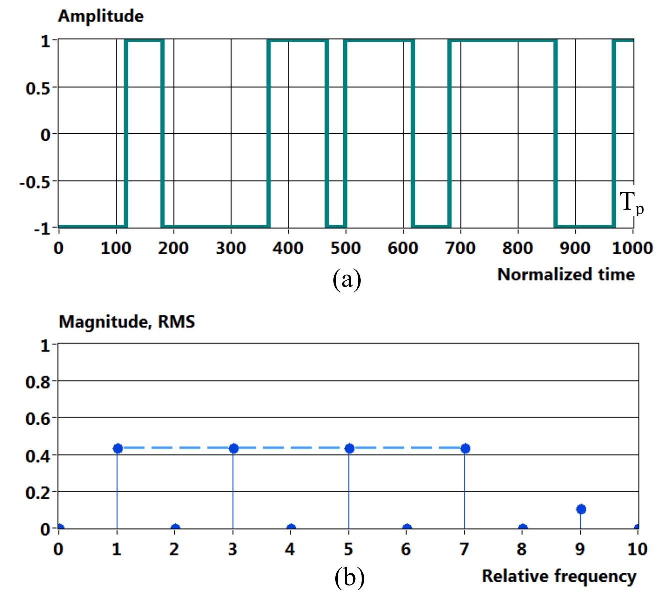

Figure 4. A synthesized binary waveform (a) and its RMS spectrum (b) with four equally emphasized components (frequency bins 1, 3, 5, 7), all of which have 0.436 RMS levels and take 76.2 % of the total signal energy.

In Fig. 5, there is given a flowchart of an exemplary edge manipulation method to create a SAS. In step 1, several initial parameters (p - signal length, number of points; B - set of required frequency grid, which are bin numbers according to the DFT standards; A - set of corresponding relative amplitudes) are provided to create the desired SAS. These parameters are determined on the bases of the current spectroscopy test requirements. The element values in the set A may be shaped by some curve, if the manipulated magnitude spectrum is required.

In step 2, the acceptable level *SQS* (Signal Quality Set) of inaccuracy of the created spectrum (the corridor into which the discrepancies of the set of actual relative amplitudes should fit in) is determined. According to the chosen signal parameters set up in step 1, the initial signal is provided in step 3 on the bases of following initial parameters: tr – total number of signal transitions, ltr – maximal length of the signal section, where non transitions occur. As a practical matter, if p is given, then tr is 10 to 100 times smaller than p, and ltr lies between 1 to $p/2$ points.

Looping algorithm begins with step 4, where the spectral properties of the initial signal are calculated. In the next step 5, these parameters are compared against the required parameter set. If the quality criteria are met for the parameter set (step 6), then the actual signal is stored (step 7).

Theoretically, within the given sequence length p, frequency content B and corresponding amplitudes A, the manipulation of edges results with all possible combinations of frequency and magnitude values. This is just the definition of the "end criteria" to select the appropriate sequence for the particular test.

In Fig. 6, a waveform and spectrum of the SAS signal with a rising slope for higher frequency components are illustrated. Compared to the signal in Fig. 4, the mean RMS value of the first 4 frequency bins is about 17 % less.

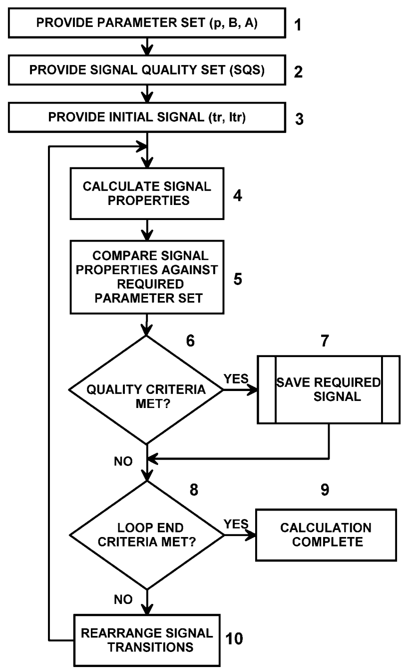

Figure 5. Flowchart of the edge manipulation method for creating binary waveforms with the required frequency content and spectrum.

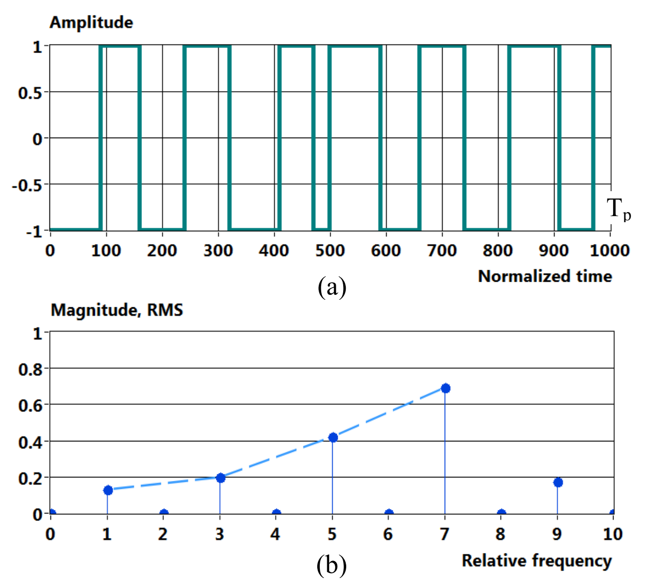

Figure 6. Waveform (a) and RMS spectrum (b) synthesized for obtaining rising levels for the first four odd frequency bins (1, 3, 5, 7), which occupy 72.5 % of the total signal energy.

Waveform and spectrum of the SAS with opposite, that is, with a falling slope for higher frequency components is a classic meander, shown already in Fig. 3.

Shaping of the magnitude spectrum can be obtained for SAS waveforms with different frequency distributions. However, the range of the magnitudes depends on the range of pulse durations, and also on the frequency distribution itself. Spectrally more sparse distributions have lesser capabilities for magnitude shaping than spectrally denser distributions. For the large number of frequency bins, the number of different pulses of the binary waveform rises vigorously, and the total number of combinations required for variation of their durations grows exponentially. Fortunately, there are possibilities for reducing the number of calculations. First, if the frequency components are odd, then the SAS waveform consists of two sets of pulses with same configuration, only their signs are opposite. Secondly, since the total waveform length is usually fixed, only these pulse lengths are usable, which enable to build up the predetermined period. The number of such pulses is less than 1 % of the total amount.

The SAS waveforms described here have signal energy concentrated on the frequencies of interest. For the comparison spectrum of the single pulse is shown in Fig. 2. Energy of the short pulse is spread over more frequency bins including a large DC component. As a consequence, energy content on the frequencies of interest makes up only 10% of the total signal energy. This is 7.6 times less than the SAS waveform shown in Fig. 4. A bipolar pulse (Fig. 7) has even less energy on the desired frequencies (8.5 % of the total one), since the energy of frequency bins 1 and 3 is lower.

If an excitation signal with the maximal energy efficiency for only a given single frequency is desired, a ternary (3-level) square wave could be used (Fig. 8). Such the signal concentrates 92.6 % of total energy onto this frequency bin.

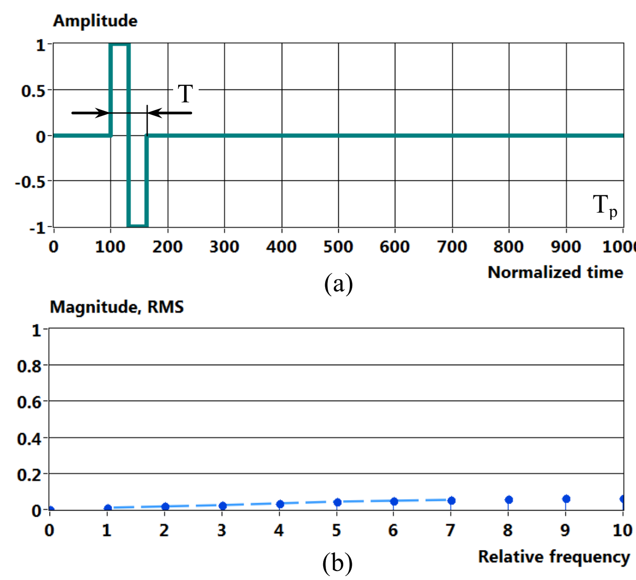

Figure 7. Waveform (a) and RMS spectrum (b) of bipolar pulse with relative duration T = (2x32/1000) T_p. Mean RMS value of the frequency bins from 1 to 7 forms merely 8.5 % of the total signal energy.

However, since the shortened square wave contains zero level sections (Fig. 8), the total energy of this waveform is 25.8 % less than of the classic meander, see Fig. 6a.

IV. Design and Construction

Implementing the above described binary signals enabled us to design and prototype a two-channel spectroscopic device (see a photo in Fig. 9), which operates simultaneously with a single (Fig. 8) or up to four (Figs. 3, 4, and 6) excitation signals with controllable spectra.

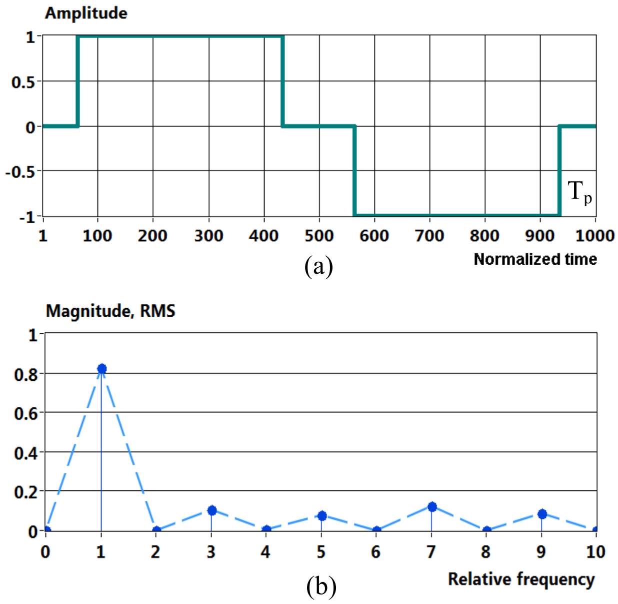

Figure 8. Waveform and spectrum of a ternary square wave optimized for concentrating the signal energy into the first harmonic component. The RMS value reaches 0.827 and seizes 92.6 % of the total energy.

The electronics is based on Texas Instruments TMS320F28069 Piccolo™ microcontroller, comprising a built-in 12-bit 3MSPS SAR Analogue-to-Digital Converter with a dual sample-and-hold unit. Also a Direct Memory Access unit (DMA) is included. Especially important is the fact that an enhanced Pulse Width Modulator (ePWM) is built in to generate complicated pulse width waveforms and sequences of binary level pulses. Also a FFT routine algorithm has been made available for this microcontroller.

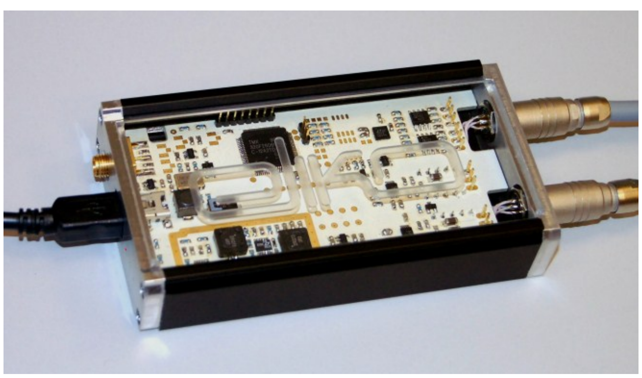

Figure 9. Prototyped spectroscopic device is based on Texas Instruments Piccolo™ microcontroller. Dimensions: 110x60x20 mm. Weight: 152 g.

A very compact and cost effective spectroscopic device has been designed on the bases of above described signal processing methods and mentioned hardware advantages. The device is implemented in single cell analysis [3], in which it gives significantly better signal-to-noise ratio than the known solutions based on pseudorandom maximum length binary sequences (MLS). Applications in cardio-vascular monitoring are just in the preparatory phase.

V. Discussion and Conclusions

A ternary excitation optimized against a single frequency component (Fig. 8), stands out by its energy efficiency: as much as 92.6 % of generated energy turns out useful. The energy efficiency of binary equal level multi-component excitation (Fig. 4) has a good level efficiency as well – about 76 %, and also the signal with rising amplitudes at higher frequencies (Fig. 6) gives an affordable result – 72.5 %. A specific attention deserves the ordinary rectangular waveform (Fig. 3) with falling spectrum at higher frequencies (efficiency is 95 %), only its applicability is limited. It should be noted that the optimization algorithm described in Fig. 5, becomes too slow at a big number of signal components. More sophisticated algorithms must be developed in this case [5–7].

The possibilities of using binary signals are not limited with those described above. For example, certain frequency band can be covered continuously by the binary chirp excitation [5], see Fig. 10.

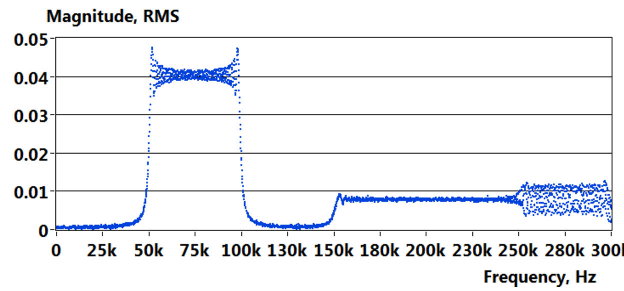

Figure 10. Continuous RMS spectrum of a binary chirp covers the frequency range from 50 to 100 kHz.

Binary signals deserve primary attention in the development of bio-impedance spectroscopy methods and devices.

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