Time-frequency impedance spectroscopy: excitation considerations

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Abstract- Alternatives to the conventional sine wave excitation in the impedance measurement technologies are studied in this paper. Measurements can be performed much faster when broadband excitation signal is applied. Using of sinc and Gaussian functions, also modifications of sinc pulses are considered. Beside the traditional sine wave and rectangular pulse excitations the carefully designed pulse wave excitation can become to a serious alternative, especially when the wide frequency range measurements, exact timing, and low energy consumption are required (laboratories on the chip, implantable and wearable devices).

I. Introduction to the problem

Measurement and analysis of the electrical bioimpedance [1] is a well established technology in wearable and implantable medical devices, e.g. in cardiac pacemakers [2]. Last time the bioimpedance method has been implemented also in nanoliter size biotechnology, e.g. in the lab-on-the-chip type devices [3]. Frequency domain analysis (spectroscopy) is typically used in bioimpedance based study and diagnosing. At the same time, the short term measurement and analysis is required, especially in cardiac applications, and even more in the high throughput bioprocessing [3]. Moreover, the moment when the spectral analysis has been done is of interest. Therefore, the joint time-frequency measurement and analysis is the aim for development of the impedance measurement methods. In this paper, the special attention is paid to one important aspect of the development – generating of excitation signals with optimal waveforms. The other important issue is generating of excitations with minimal energy. This is especially important for applications in battery powered implantable devices, but more generally as well – the excitation energy is always restricted when measuring biological subjects.

A. Waveforms of excitation signals

A generalised system for bioimpedance measurement and analysis is given in Fig. 1. An excitation generator G generates an AC excitation current $i_e(t)$, which is injected into the complex impedance $\dot{Z}$ to be measured and analysed. Z_p depicts the impedance of the excitation path including electrodes. The response to the excitation - voltage $v_r(t)$ - carries information about the impedance $\dot{Z}$. This information will be analysed in an impedance analyser (classically in frequency domain, but also a time domain analysis is introduced). As a result, both, the spectral and time based parameters of the impedance behaviour will be obtained – $\dot{Z}(\omega, t)$. Typically the sine wave excitation with changeable frequency is in use. To accelerate the measurement process, simultaneous multisine measurements have been introduced in some cases.

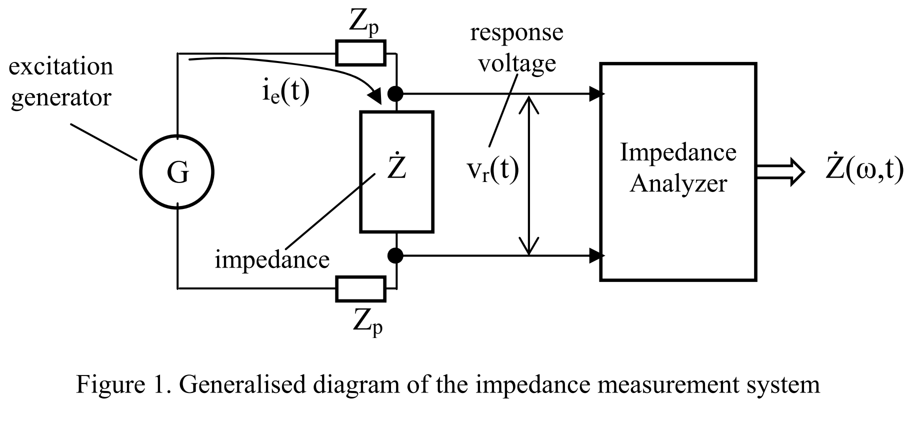

Figure 1. Generalised diagram of the impedance measurement system

To cover the whole frequency range in a short measurement slot, also narrow rectangular wave pulses have been generated for wideband excitation [4]. This method is fast and can follow the time domain changes, but has at least two drawbacks. First, to obtain the equal spectral density at all the frequencies under interest, the excitation pulse must be very short. As a result the spectral density of excitation will be low. Second, only a part of the pulse energy is concentrated into the frequency range of interest, another part falls outside of this range (to the higher frequencies).
Our aim is to find such the waveforms for excitation pulses, energy of which is concentrated exactly into the frequency range of interest, whereas the measurement process must be done during a short and well determined time interval.

B. Comparison of sinc and Gaussian pulses

The sinc function sin(ωt)/(ωt), see Fig.2a, has a band limited rectangular spectrum, which is determined by the frequency $\omega = 2\pi f$ of the sine function, see Fig.2, c and e. In principle, the sinc function has exactly rectangular spectrum only then, when its duration extends to infinity. In Fig.2a is shown a practical case (shortened function), where the spectrum is not ideally rectangular, but however acceptable. Only about 2% of the excitation energy drops outside the bandwidth of interest. Due to the certain important properties of Gaussian function (spectrum is also the Gaussian function and some others), the pulses with Gaussian waveform (see Fig.1b) are of interest.

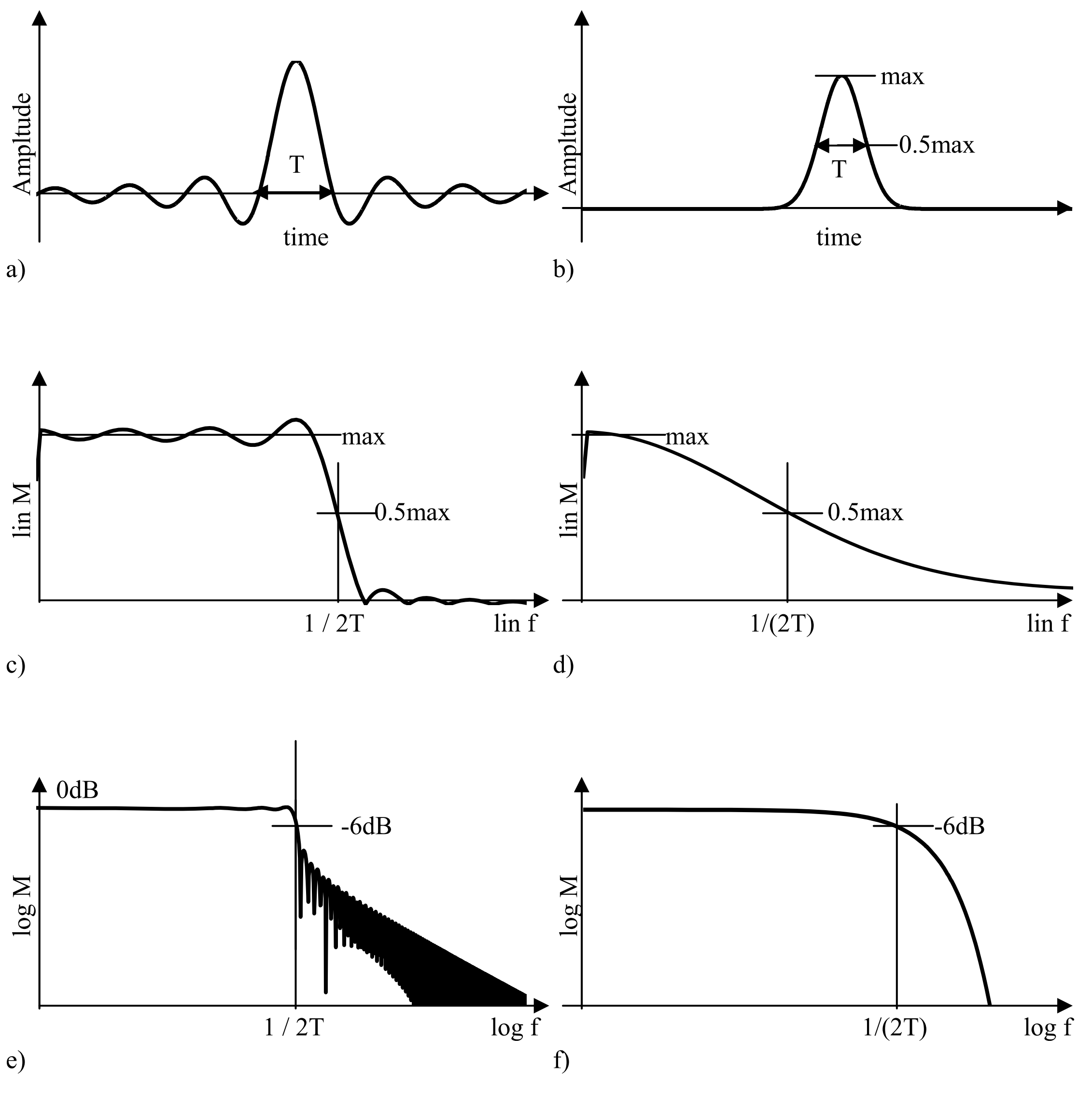

Figure 2. Excitation pulses and their spectra: a) sinc function, b) Gaussian function, c) and e) - spectrum of the sinc function, d) and f) - spectrum of the Gaussian function

But the analysis shows that roughly 30% of excitation energy will fall outside the bandwidth in this case (see also Fig.1d and f). Therefore, this type of excitation goes out of our interest. By the way, using of short rectangular pulses results in nearly 40% losses of the excitation energy.

II. Using of modified sinc pulses for excitation

Excitation of biological subjects must avoid any DC current flow through the tissue under study. Therefore, the haversinc function $\sin^2(\omega t)/(\omega t)$, see Fig.3a, is proposed by the authors of this paper. Its spectrum in Fig.3b is similar to the spectrum of original sinc pulse in Fig. 2c, but does not contain the DC component.

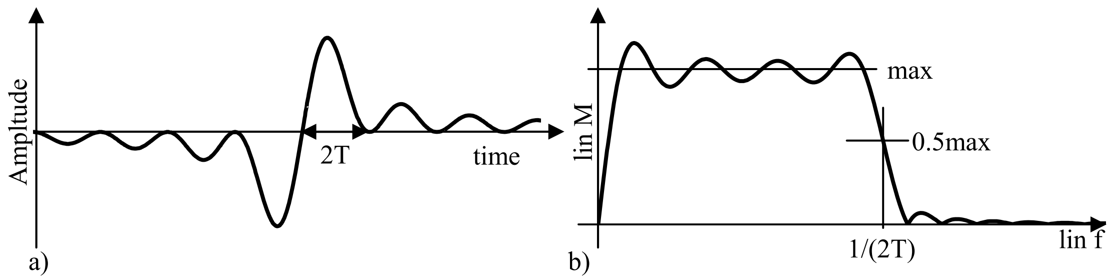

Figure 3. Haversinc excitation pulse (a) and its spectrum (b)

When the frequency range of interest does not cover the lower band of frequencies, then it is reasonable to implement the excitation pulse, which is composed by multiplication of the sine wave carrier signal $\sin(\omega_c t)$ with the sinc pulse $\mathrm{sinc}(\omega_s t)$, see Fig.4a. The spectrum of such the signal (Fig. 4b) is centred to the frequency f_c to and covers the range from (f_c- f_s) to (f_c+ f_s). Using of rectangular windowing function in Fig. 4b means simple shortening of the sinc function, see Fig.2a. Applying a much complicated windowing as the Blackman-Harris function, gives the smooth excitation spectrum (Fig.4b), which results in the much better determined response to the excitation.

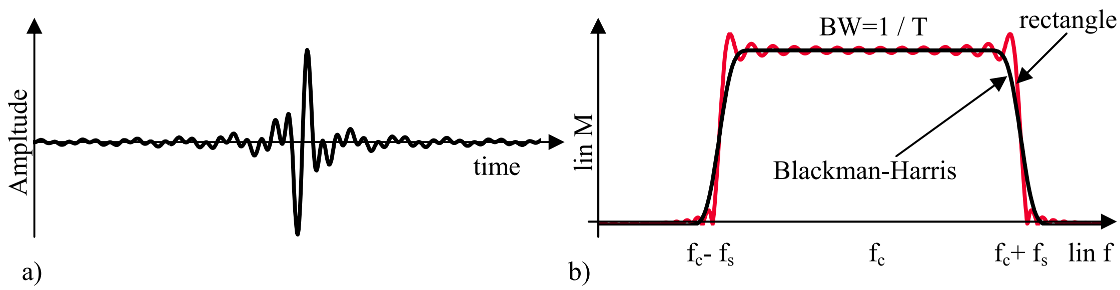

Figure 4. A modified excitation pulse and its spectra: a) sine wave carrier modulated by sinc function, and b) its spectrum using two windowing functions

III. Possible applications

Impedance spectroscopy has long been used to study cell suspensions and bulk tissues. In the impedance spectroscopic flow cytometer the complex impedance is measured for each cell at several simultaneous frequencies, and the measurements are averaged over the entire population [3]. Measurements in different frequency regions will provide information about the dielectric properties of the cells and biological tissue [3, 4]. The amplitude and phase information can be used to characterize and separate the cells, depending on their dielectric properties.

Although the particle velocity in the flow cytometer is currently 10 mm/s [3], optimization of the system is needed to increase the throughput and measurement sensitivity.

The proposed set of excitation pulses with broadband spectrum suits well to improve the behaviour of the impedance spectroscopy applications (see Fig.5), where wide frequency range characterization of the test samples is required.

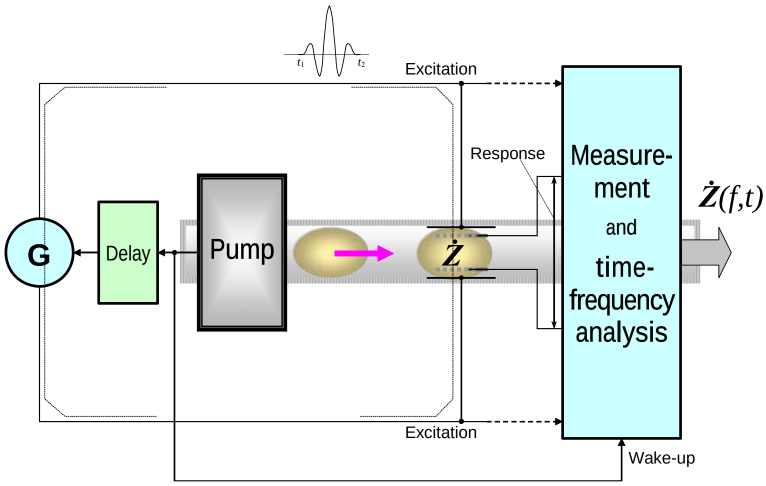

Figure 5. Diagram of the impedance spectroscopy flow cytometer

III. Discussions and Conclusions

Every excitation signal has its advantages and disadvantages in practical implementations. The Gaussian pulse is simple but too much energy falls out of the frequency range of interest. The sinc function has a nice flat spectrum, but the crest-factor is too large. The chirp excitation is probably most favourable when the small crest-factor is required. Signals like haversinc pulses and modified sinc pulses are more favourable when the absence of the DC component is crucial.
All pulse wave excitation signals have a broadband spectrum and therefore the noise level in the response signal can be relatively high. Therefore, in order to obtain intensive broadband spectrum the amplitude of excitation pulses must be relatively high which may cause the problems when the test sample has a nonlinear character.
Carefully designed pulse wave excitation can become to a serious alternative (besides the traditional sine wave and rectangular pulse excitations), especially, when the fast measurements with exact timing are required to perform in the wide frequency range, and when the energy consumption is important. The theoretical expectations were verified using an electrical phantom of bioimpedance, an arbitrary waveform generator AFG3252 as the excitation source, and a digital oscilloscope DPO4104 with spectral analysis for measurement and analysis (both from Tektronix). The results confirm that the described excitation signal pulses can become to a serious alternatives to the conventional ones.

Acknowledgements

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References

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