Simplified signal processing for impedance spectroscopy with spectrally sparse sequences

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Abstract. Classical method for measurement of the electrical bio-impedance involves excitation with sinusoidal waveform. Sinusoidal excitation at fixed frequency points enables wide variety of signal processing options, most general of them being Fourier transform. Multiplication with two quadrature waveforms at desired frequency could be easily accomplished both in analogue and in digital domains, even simplest quadrature square waves can be considered, which reduces signal processing task in analogue domain to synchronous switching followed by low pass filter, and in digital domain requires only additions. So called spectrally sparse excitation sequences (SSS), which have been recently introduced into bio-impedance measurement domain, are very reasonable choice when simultaneous multifrequency excitation is required. They have many good properties, such as ease of generation and good crest factor compared to similar multisinusoids. Typically, the usage of discrete or fast Fourier transform in signal processing step is considered so far. Usage of simplified methods nevertheless would reduce computational burden, and enable simpler, less costly and less energy hungry signal processing platforms. Accuracy of the measurement with SSS excitation when using different waveforms for quadrature demodulation will be compared in order to evaluate the feasibility of the simplified signal processing. Sigma delta modulated sinusoid (binary signal) is considered to be a good alternative for a synchronous demodulation.

1. Introduction

Complex electrical impedance has been widely used to characterize properties of biological tissues for many years [1]. One of the promising application areas is postoperative monitoring of the healing process. Bioimpedance reflects changes in the tissue state, which can be used to characterize the revivability or resuscitation ability of the tissue. Typically simultaneous measurement at several frequencies is required. Low and high frequency currents flow through the resistive interstitial space between the cells (extracellular component), but only the high frequency current can flow through the electrical capacitances of the insulating cell membranes (intracellular current). Ratio of these currents will reflect the state of the cells, accumulation of fluid in extracellular space, amount of swelling and ultimately warn before massive edema is about to develop. Generally it is desirable to monitor tissue parameters from different tissue locations simultaneously. These multifrequency and multisite measurements may be relatively rare and slow due to the dynamics of the underlying processes, and can be even sequential. Monitoring is warranted during the first few days after the surgical intervention, and possible changes take several minutes to occur. One of the critical tasks is restoration of the spontaneous blood circulation postoperatively. Cardiac activity will cause modulation of the

measured bioimpedance due to varying amounts of blood pushed through the tissue. Therefore faster changes in impedance need to be monitored as well, in order to assess whether the blood vessels are connected, and blood flow is restored. Extensive laboratory experiments have been conducted during longer period on isolated tissue samples, such as pigs heart, tongue etc. of pigs, for preclinical investigation of the impedance changes in the biological tissues. Device prototype has been developed for conducting these bioimpedance measurements in laboratory conditions (figure 1). Device has the ability to conduct measurements simultaneously on 16 frequencies in the range from 1 Hz to 100 kHz. Spectrally sparse sequences have been proven to be viable excitation signals for such a device [2]. SSS as two level or binary signal has many good properties, such as ease of generation, and good crest factor compared to similar multisinusoids. They can have tens of almost arbitrarily chosen, spectral lines with tailored magnitudes. The drawback is that there is also certain amount of energy on unwanted spectral lines, on so called snow lines, which extend well beyond the highest measurement frequency of interest. Combination of oversampling and correction is used in order to avoid large measurement errors. Another drawback is that real time calculation of that many discrete Fourier coefficients puts a heavy burden even on the internal resources of the used digital signal processor (DSP) and has been main limiting factor so far. Therefore simplification of the signal processing step is highly desirable.
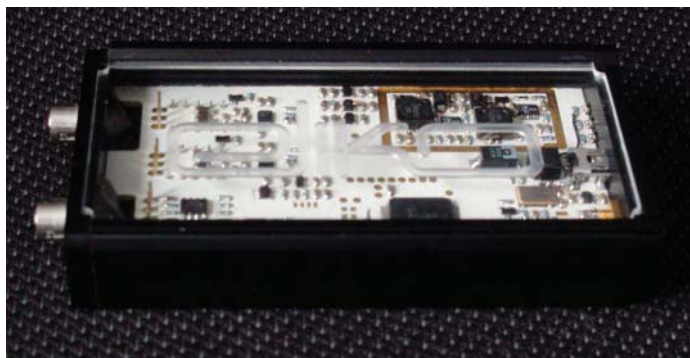

Figure 1. Two channel tissue monitor with spectrally sparse sequence as an excitation signal.

2. Description of simplification steps and the test

One of the possibilities is replacement of the sinusoidal signals used for quadrature demodulation with suitable binary counterparts. In an essence it would enable usage of simple summation (or switching in analogue domain) instead of more complex multiply and accumulate (MAC) operations. Eliminating MAC from the signal processing chain widens choice of possible signal processing platforms. It has been shown that simple low power complex programmable logic device (CPLD) can be used to process acquired signals if only summation is involved [3]. Three of the possible candidates are considered for replacement, and resulting measurement errors are compared (figure 2, table 2). First is the set of simple quadrature square waves, second is the set of shortened square waves (SSW) [3] with shortening angle of 22.5 degrees, and lastly sinusoids modulated with first order sigma delta circuit are considered. Simple first order RC low pass circuit is used with varying corner frequency to make simulations in LabVIEW environment more realistic, since impedance of various biological tissues can be modelled as RC circuitry. Filter corner frequency is swept form 1 Hz to 1.1 kHz, covering wide variety of possible target impedances. SSS, used in simulation, contains ten measurement frequencies (2, 4, 8, 16, 32, 64, 128, 256, 512, and 1024 Hz) with equal magnitudes. Result of the demodulation of the response to the SSS excitation with binary signals is compared against measurements with classical single sinusoidal excitation signal which is demodulated by multiplying it with two quadrature sinusoids.
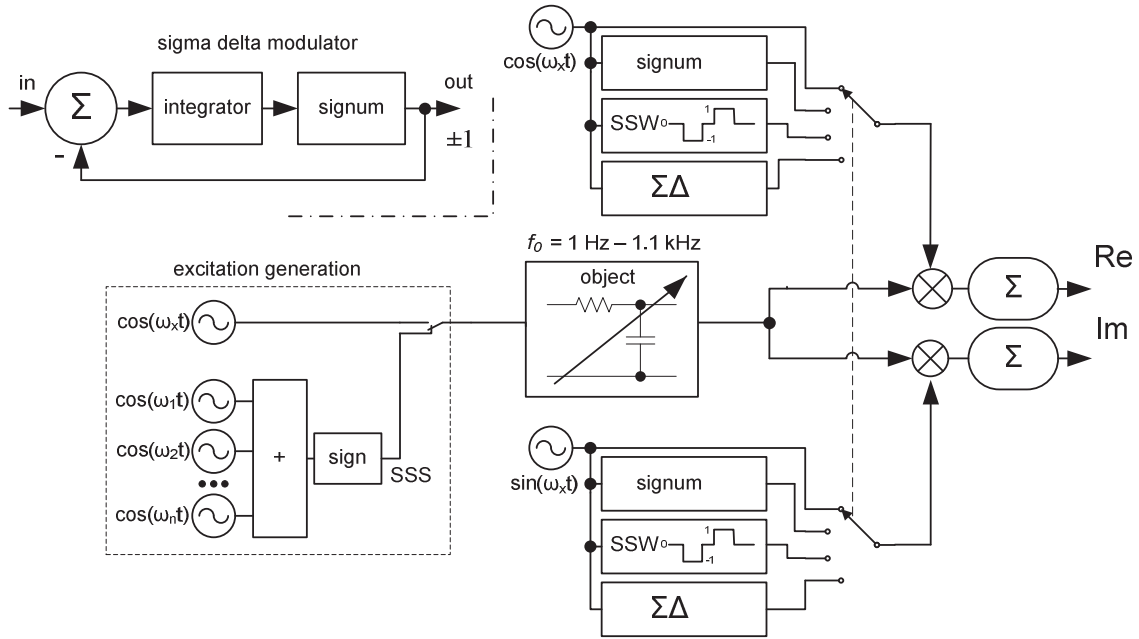
Figure 2. Simplified first order sigma delta modulator (upper left), and block diagram of the experiment with excitation generation, object and demodulation, where f_0 is filter corner frequency, ω_1 - ω_n frequencies of the SSS components, and ω_x is an actual measurement frequency.

Quadrature sinusoids were also used for demodulation of the response to SSS excitation, however resulting errors were very low compared to purely sinusoidal case, and are therefore omitted from analysis. It should be noted that results are not general and depend on chosen excitation sequence, nevertheless similar tests can be conducted for any arbitrary sequence needed and results compared.

3. Results

Since RC circuit is modelled using exponential function certain caution is in order. Measured real and imaginary components of the response signal should be equal exactly when the corner frequency of the sweeping RC filter coincides with the measurement frequency. In reality there is some discrepancy between these frequencies due to limited resolution of the simulation. To assess simulation accuracy this discrepancy is calculated for purely sinusoidal measurement case:

Table 1. Measurement frequency versus frequency when real and imaginary parts coincide in case of sinusoidal excitation and demodulation with sinusoidal signals.

$f_{sampling}$, kHz	Frequency when real and imaginary parts coincide in Hz									
	Measurement frequency in Hz									
	2	*4*	*8*	*16*	*32*	*64*	*128*	*256*	*512*	*1024*
100	1.99	3.99	7.99	15.97	31.92	63.74	126.9	251.9	495.8	960.8
1000	1.99	3.99	7.99	15.99	31.99	63.99	127.9	255.6	510.3	1017.4

The sampling frequency should exceed maximal filter corner frequency roughly 1000 times according to table 1. Raising it further would make simulation too slow to complete within reasonable time.

Generally relative errors are presented in literature, whereas deviation from the correct value is divided by the correct value. In some cases these errors exceed 50% for real and imaginary parts.

However closer examination shows that it happens when the value of the measurand is very small. In real measurement situation it could mean that it is already buried in the noise. Therefore it seems reasonable to compute full scale errors instead, whereas deviation from the correct value is divided by maximal value of the measurand. Resulting errors are shown in table 2. Also absolute phase errors in degrees are included in italics for better clarity.

Table 2. Demodulation quality with square wave (SQW), shortened square wave (SSW), and sigma delta modulated sinusoid is compared against demodulation of the response to the sinusoidal excitation with pure sinusoids. Errors below 0.001% are denoted by "-". Absolute phase errors are added in italic.

Signal component detected, signal used for detection	Maximal full scale measurement error in % / *absolute phase error*									
	Measurement frequency in Hz									
	2	*4*	*8*	*16*	*32*	*64*	*128*	*256*	*512*	*1024*
Re, SQW	1.42	3.85	3.23	3.48	2.65	2.80	1.95	0.048	0.63	0.47
Im, SQW	3.24	5.00	5.27	2.89	1.79	1.32	0.22	0.85	0.55	1.22
Magnitude, SQW	1.36	3.85	3.23	3.48	2.64	2.78	1.93	0.18	0.39	0.38
Phase, SQW (deg, abs)	*0.96*	*1.55*	*1.63*	*1.00*	*0.61*	*0.55*	*0.2*	*0.25*	*0.29*	*0.48*
Re, SSW	3.81	2.60	2.36	2.52	1.54	0.81	0.85	0.42	0.32	0.27
Im, SSW	1.11	1.79	2.13	1.81	1.77	1.10	0.15	0.29	0.92	0.54
Magnitude, SSW	3.81	2.60	2.36	2.52	1.52	0.78	0.83	0.36	0.05	0.15
Phase, SSW, (deg, abs)	*0.24*	*0.56*	*0.63*	*0.56*	*0.56*	*0.34*	*0.09*	*0.14*	*0.33*	*0.23*
Re, sigma-delta	0.002	0.007	0.006	0.001	-	0.024	-	0.005	0.004	-
Im, sigma-delta	0.005	0.005	0.01	0.02	0.007	0.009	0.005	0.004	0.003	0.007
Magnitude, sigma-delta	0.002	0.007	0.006	0.001	-	0.024	-	0.005	0.004	0.003
Phase, sigma-delta, (deg, abs)	*0.002*	*0.002*	*0.004*	*0.006*	*0.004*	*0.002*	*0.002*	*0.003*	*0.004*	*0.12*

4. Discussion

Even though error calculation results depend on actual SSS used, and on actual object to be measured, some observations are in order. First of all, when comparing measurement results with those of pure sinusoidal excitation and classical Discrete Fourier Transform (DFT), SSS perform almost exactly as well when DFT is applied. Secondly, sufficient oversampling is in order when SSS is used for measurement, due to higher harmonic content. Regarding demodulation with different binary signals it is probably fair to say that sigma delta modulated sinusoids perform almost as well as real sinusoids, with both relative and full scale magnitude errors being below 0.1% and absolute phase error below 0.2 degrees. Even measurement results with simple square waves are within 4% of actual magnitude and 2 degree of real phase. Question remains if the usage of shortened square waves is justified due to little improvement over simple square waves, and added complexity.

5. Acknowledgments

References
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