A DFT-BASED MULTIFREQUENCIAL
COMPLEX BIOIMPEDANCE ANALYZER

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Abstract: Bioimpedance reflects important biological and clinical information. It has received attention because it is a non-invasive, safe and fast method. The Discrete Fourier Transform method and the principle of undersampling were used to obtain the magnitude and phase angle of complex impedance measurements. We describe the development of prototype of a bioimpedance analyzer. Experiments were done using resistive and capacitive loads and also, in vivo measurements. The prototype is capable of measuring complex impedance values from 1 Ω to 50 kΩ in the frequency range from 50 Hz to 1 MHz ,with 2.9 % of magnitude and 0.69 of phase angle mean errors. Results confirm the feasibility and efficacy of the proposed methodology.

Key-words: Bioimpedance, Discrete Fourier Transform, Undersampling, Measurement, Instrumentation

Measurement Method

Bioimpedance devices use a magnitude and phase constant current source to generate a small voltage through the patient’s body. This voltage is measured using a differential instrumentation amplifier and further treated with digital or analog techniques.

The prototype described in this paper uses the DFT method to extract both real (x) and imaginary (y) components of a sampled signal. To obtain these values, it is necessary to know only the period of the analysed wave and the sample rate, as follows:

\[
x = \frac{2}{N} \sum_{k=0}^{N-1} s(k) \cos \left( 2\pi \frac{kT}{T} \right)
\]

\[
y = \frac{2}{N} \sum_{k=0}^{N-1} s(k) \sin \left( 2\pi \frac{kT}{T} \right)
\]

where \(N\) is the total number of samples, \(k\) is the index of a sample, \(t\) is the time between samples, \(s(k)\) is the sampled value and \(T\) is the period of the wave.

After finding \(x\) and \(y\) it is possible to obtain the magnitude (\(A\)) and phase angle (\(\theta\)) by simple transformations, as follows:

\[
A = \sqrt{x^2 + y^2}
\]
\[
\theta = \arctan \left( -\frac{y}{x} \right) \quad (4)
\]

**Development of the Prototype**

Figure 1 shows a block diagram of the proposed multifrequencial bioimpedance analyzer. In this prototype, we used a tetrapolar configuration for electrodes, in such a way that electrodes’ impedance influence is largely reduced.

The circuit consists of an oscillator, a magnitude and phase constant current source, an amplifier module, a sample-and-hold circuit, a microcontroller, a keyboard, a graphic display and a serial interface. Because all signals are processed digitally, the analogical circuit does not need to be complex. A Direct-Digital Synthesizer (DDS) was chosen to generate the sine waves from few mHz up to 1 MHz. This circuit offers high precision frequencies, thermal stability and requires only a 32 bits digital word to be programmed.

To protect patients against electric hazards, and also to avoid tissue heating, a magnitude and phase constant current source of \(800 \mu \text{A}\) was used. The voltage generated in the patient as a consequence of that current flow is measured through an association of fast differential amplifiers, digitally programmed for a maximal gain of 160. The preliminary version of the prototype does not have electrical isolation of the patient, but future versions will incorporate this feature.

The prototype was designed to acquire signals at a maximum sampling rate of 13 kHz. Therefore, based on the Nyquist rule, the maximum frequency of the measured signal is 6.5 kHz. On the other hand, the range of frequencies with relevant information for bioimpedance analysis is 10 kHz to 500 kHz. In order to overcome this serious limitation, and to allow measurements of signals of higher frequencies, we used the principle of undersampling. This method consists in using sampling rates lower than twice the frequency of the input signal. Although the resulting sampled signal is of a much lower frequency than the input signal, it still contains the same phase and amplitude information as the original one [9], as is illustrated in Figure 2. The only requirement to use DFT with undersampling is to have a fast tracking time, which is satisfied with the addition of a sample-and-hold circuit at the inputs. To improve measurement accuracy, a variable sampling period \(T_s\) was used, as shown in equation 5:

\[
T_s = T_{s_{\text{min}}} + \frac{T}{sc} \quad (5)
\]

where \(T\) is the measured period of the waveform, \(T_{s_{\text{min}}}\) is the hardware smallest sampling period, and \(sc\) is the desired number of samples per signal cycle.

![Figure 1: Block diagram of the prototype.](image1)

The core of the prototype used a C8051C020 processor running at 25 MHz. This processor is capable of achieving 25 MIPS and has 64kBytes of internal flash RAM program memory, besides eight 8-bits input/output ports and a 100 ksamples 12-bits analog/digital converter. The operational system was developed in ANSI C programming language, using both Keil compiler/linker (http://www.keil.com) and the Cygnal IDE development system (http://www.silabs.com). The user interface consists of a keyboard and a graphic LCD (68 x 240 dots) for plotting curves of resistance/capacitive reactance versus frequency.

**Experiments**

Due the small value of \(800 \mu \text{A}\) that flows through patients body, physiological artefacts and circuit’s parasites currents can be relevant noise sources, making difficult the measurements. A technique to improve the accuracy of the circuit is to repeat measurements and compute the mean value. This technique is similar to promediation, commonly used in digital signal processing [10]. Empirical tests showed that using 20 repetitions, the prototype presented good performance and still a fast response time.

The prototype was compared with calibration equipment LCZ KC-548, produced by Kokuyo Testing Instruments & Systems. The first evaluation essay was done with purely resistive loads (0.1% accuracy). Because these loads have a small phase angle, it was possible to study the circuit’s phase response. Normally, bioimpedance measurements are lower than 10 k\(\Omega\). That is why the equipment was projected for small resistance values. The variation of magnitude and phase angle errors with frequency for a 100 \(\Omega\) resistive load is...
shown in Figures 3 and 4, respectively. For both curves, the prototype displays a good accuracy, when compared with commercial equipment.

![Figure 3: Magnitude measurement errors versus frequency for a pure resistive load of 100 Ω.](image)

Although errors in undersampling increase proportionally to the frequency difference, it is possible to see that the prototype performance is still satisfactory, even at 1 MHz. For each resistance the magnitude and phase angle mean error for frequency sweepings from 50 Hz until 1 MHz are plotted in Figure 5.

Changing test resistance values, magnitude errors appear most often, but phase angle response stays almost constant throughout the whole range. For loads smaller as 1Ω, measurement differences increase due to the A/D converter resolution and the limitation of gain of the input amplifiers. For high values of resistances, amplifiers input impedance is the mainly error source.

As result of this essay, it is possible to conclude that the developed prototype is able to measure complex impedance values from 1Ω to 50 kΩ in the frequency range from 50 Hz to 1 MHz with 2.9% of magnitude and 0.69 of phase angle mean errors.

![Figure 5: Magnitude and phase mean error for frequencies from 50 Hz to 1 MHz.](image)

Capacitance and inductance measurements were also done, allowing to verify equipment’s phase angle accuracy. It was possible to measure angles from -180 to +180 degrees.

Real bioimpedance measurements of 10 volunteers were done with frequencies from 10 kHz to 1 MHz. Measurements followed the standard protocols for patient security. Figure 6 shows the measurements of in vivo impedance for a given subject. Signal electrodes were placed in the back of hands and feets, and measurement electrodes were fixed approximately 4 centimeters far from signal electrodes, inwards. This configuration is aimed at measuring the total body impedance (TBI). Almost all measurements corresponded to the expected results for healthy people. Aware of the possible errors introduced, in these measurements, the intrinsic impedance of cables and electrodes were neglected.

![Figure 6: In vivo impedance measurements from 10 kHz to 1 MHz.](image)

**Conclusions**

Although the prototype presented satisfactory results regarding accuracy, many improvements can still be implemented so as to enhance performance. The input impedance of the amplifier block could be increased by adding amplified buffers to each electrode, allowing measurements of loads as higher as 50 kΩ.

The improvement of processing time is also a desired feature, which is possible through the decrement of the sampling period of the A/D converters and the replacement of current processor by another one of higher clock. A faster sampling rate would also allow the measurement of impedances in a wider frequency range. This can be achieved by replacing the current DDS, which maximal output signal frequency is limited in 12.5 MHz. Bipolar inputs in the A/D converters can minimize the number of amplifier stages in the system, thus contributing to increase the response time. Another advantage of such component is the high immunity against undesired offsets. Besides, a resolution of 14 bits could already eliminate the programmable gain amplifiers. If the A/D converters could sample 2 channels simultaneously, circuit costs would be minimized by eliminating sample-and-hold circuitry.

An alternative to compensate circuit drawbacks is the development of use self-correcting algorithms. This
is possible by finding an equation that represents phase and modulus measurements response curves. Analyzing the essays it was possible to verify that undersampling associated with DFT algorithm allowed the prototype to measure signals with frequencies up to 38 times higher as the maximum sampling rate, Therefore, this is a promising technique to be used in bioimpedance measurements.

We believe that the techniques used here are efficient and the multifrequency complex bioimpedance analyzer described could be reproduced by other researchers using the same technique.

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References


