A DFT-BASED MULTIFREQUENCIAL COMPLEX BIOIMPEDANCE ANALYZER

Carlos E. Amaral [1], Heitor S. Lopes

Bioinformatics Lab./CPGEI, Federal University of Technology – Paraná (UTFPR)
Av. 7 de setembro, 3165 80230-901 Curitiba, Brazil
e-mail: hslopes@pesquisador.cnpq.br

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

Introduction

Living tissues have characteristic impedances similar to resistive and capacitive circuits. With the application of a small electric current, ionic currents flow through cells, organs and even the whole body. Therefore it is possible to analyze frequency spectra of biological elements. Many researches have demonstrated that bioimpedance reflects important information, such as cardiac and respiratory frequency, total body water volume, body lean mass and body fat mass [1]. Also, it is known that measurements of bioimpedance in low frequencies are related to the amount of extracellular water. On the other hand, measurements in high frequencies reveal the intracellular water contents.

The main advantages of bioimpedance are: ready response, it is safe and does not require expensive circuitry. Besides, bioimpedance is non-invasive, since electrodes are put over the patient's skin. Many methods are available to measure complex impedance components such as Lissajous figure, signal multiplication [2], phase-locked loop (PLL), lock-in amplifier [3,4], step-response [5] and Discrete Fourier Transform [6,7]. Most commercial equipments can measure bioimpedance magnitude and phase in a single frequency (usually, 50 kHz), thus limiting the range of possible analyses [8].

This work proposes the association of the Discrete Fourier Transform (DFT) algorithm with an undersampling technique to measure bioimpedance in a wide range of frequencies. As result of this study, a multifrequencial complex bioimpedance measurement prototype was constructed and evaluated.

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:

$$x = \frac{2}{N}\sum_{k=0}^{N-1} s(k).\cos\left(2\pi\frac{k.t}{T}\right) \quad (1)$$

$$y = \frac{2}{N}\sum_{k=0}^{N-1} s(k).\sin\left(2\pi\frac{k.t}{T}\right) \quad (2)$$

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 (θ) by simple transformations, as follows:

$$A = \sqrt{x^2 + y^2} \quad (3)$$

[1] Currently with Lehrstuhl für Medizinische Elektronik, Technische Universität München.

$$\theta = \arctan\left(\frac{-y}{x}\right) \quad (4)$$

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 μA 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.

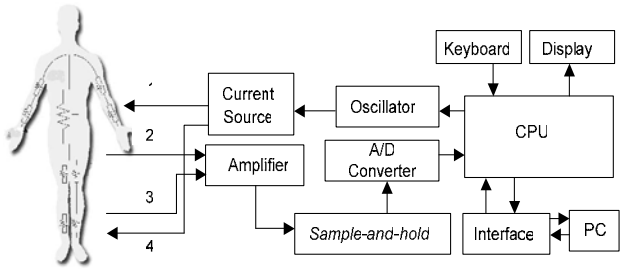

Figure 1: Block diagram of the prototype.

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 overcame 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 (*Ts*) was used, as shown in equation 5:

$$Ts = Ts_{\min} + \frac{T}{sc} \quad (5)$$

where T is the measured period of the waveform, Ts_{min} is the hardware smallest sampling period, and sc is the desired number of samples per signal cycle.

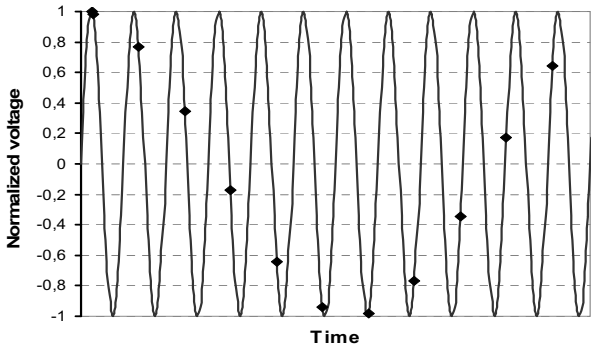

Figure 2: Undersampling a 1 kHz signal.

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 μA 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 kΩ. That is why the equipment was projected for small resistance values. The variation of magnitude and phase angle errors with frequency for a 100 Ω resistive load is

shown in Figures 3 and 4, respectively. For both curves, the prototype displays a good accuracy, when compared with commercial equipment.

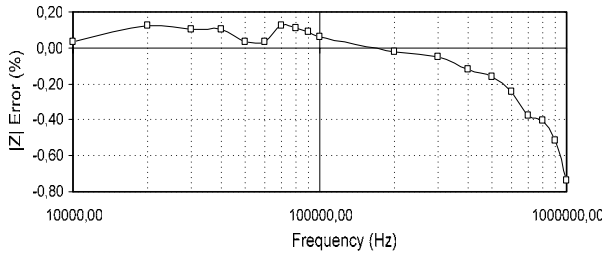

Figure 3: Magnitude measurement errors versus frequency for a pure resistive load of 100 Ω.

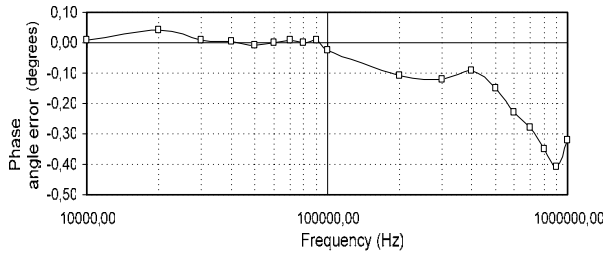

Figure 4: Phase angle measurement errors versus frequency for a pure resistive load of 100 Ω.

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 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.

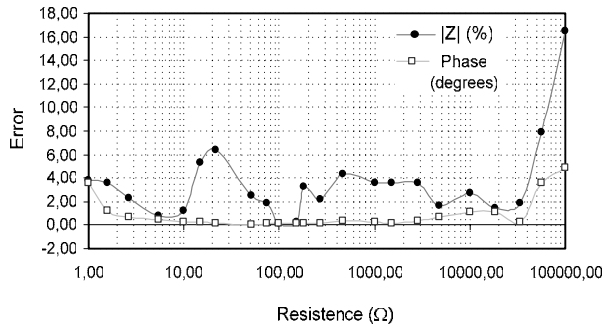

Figure 5: Magnitude and phase mean error for frequencies from 50 Hz to 1 MHz.

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 aproximately 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.

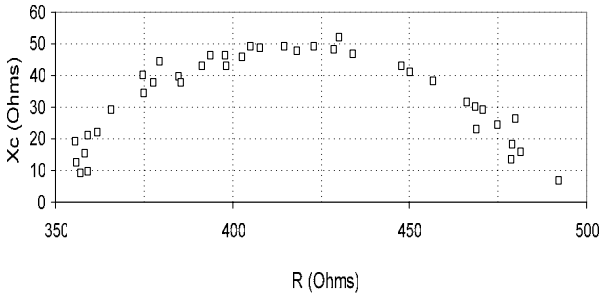

Figure 6: *In vivo* impedance measurements from 10 kHz to 1 MHz.

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 multifrequencial complex bioimpedance analyzer described could be reproduced by other researchers using the same technique

Acknowledgement

H.S. Lopes acknowledges the financial support by the Brazilian National Research Council (CNPq) under research grant 305720/04-0.

References

[1] Geddes, L.A., Baker, L.E. (1989), *Principles of Applied Biomedical Instrumentation*, 3rd edition, New York: John Wiley & Sons, p.537 –651.

[2] Grimnes, S., Martinsen, G.O. (2000), *Bioimpedance and Bioelectricity Basics*, London: Academic Press.

[3] Ackmann, J.J. (1993), "Complex bioelectric impedance measurement system for the frequency range from 5 Hz to 1 MHz" *Annals of Biomedical Engineering*, v. 21, n. 2, p. 135–146.

[4] Min, M., Märtens, O., Parse, T. (2000) "Lock-in measurement of bio-impedance variations" *Measurement*, v. 27, n. 1, p. 21–28.

[5] Neves, C.E.B., Leite, B.B., Souza, M.N. (2000), "Body Impedance spectroscopy based on a step response" *Physiological Measurements*, v. 21, n. 3, p. 395–408.

[6] Funaki, T., Matsuura, K., Tanaka S. (2000), "Error estimation and correction of detected phase by real time DFT*" Transactions of IEE of Japan*, v. 120-B, n.12, p. 1682–1690.

[7] López, M.G., Madrid, R.E, Felice, C.J. (2001), "Medidor de biomasa por espectroscopia dieléctrica", In: *Anales del XIII Congreso Argentino de Bioingeniería*, Tucumán, Argentina, p.327.

[8] Thomasset, A.L. (1997), "Bio-electrical impedance analysis", Available in: http://home.worldnet.fr/~althomas/HomePage.shtml.

[9] Pérez, P., Santos, A., Vaquero, J.J. (2001), "Potential use of the undersampling technique in the acquisition of nuclear magnetic resonance signals" *Magnetic Resonance Materials in Physics, Biology and Medicine*, v. 13, n. 2, p. 109–117.

[10] Webster, J.G. (1999), *The Measurement, Instrumentation, and Sensors Handbook*, Boca Raton, FL: CRC Press.