Comparative Analysis of Multisine and Binary Excitation Signals for Human Body Analysis

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Abstract— Bioimpedance analysis (BIA) is a potential field and clinical method for evaluating fat percentage and body mass. Multi-frequency bioimpedance monitoring methodology used for the analysis purpose is a widely used method to estimate body composition. The multifrequency bioimpedance analysis using network analyzer is a relatively quick, simple and non-invasive technique to measure body composition. The multisine and binary waveforms can be used as multifrequency excitation signals in measurement of impedance spectrum of biological objects. By adjusting the phases of the desired spectral components the multisine excitation signal can be optimized.

Keywords— Multifrequency, Multisegment, Multisine, Binary waveforms.

I. INTRODUCTION

Bioimpedance is the response of a living organism to an externally applied electric current. It is the opposition to the flow of electric current through the tissues. The measurement of the bioimpedance of the humans and animals has proved useful as a non-invasive method for measuring such things as blood flow and body composition like fluid content and fat content. Bioimpedance body composition models, which has become popular under the term Bioelectrical Impedance Analysis (BIA) and Bioelectrical Impedance Spectroscopy (BIS)[1,2]. Different measurement techniques and various bioelectrical properties form a collection of methods that are employed for multiple applications. Generally, these methods can be classified according to the following four groups: transimpedance, transmission line, microwave, inductive and finally a combination of the preceding. Furthermore, all methods can be based on either single- or multiple-channel measurements.

Bioimpedance spectroscopy is based on the measure of the voltage drop across body segments crossed by an injected current. The voltage drop is due to the internal resistance of the body cells. When a certain amount of frequency is passed through a body segment it takes the least resistive path. For low frequency signal the current avoids the intracellular space and passes from the extracellular fluids because fluids provide less resistance as compared to the cell membrane. In case of high frequency signals the current passes directly through the intracellular water. Due to the nature of tissues, the impedance may vary with the frequency of measuring signal. The impedance decreases as the frequency increases. The relationship between the frequency and impedance is nonlinear. The resistivity and permittivity both are frequency dependent. Higher the frequency, lower is the impedance.

There are a number of commercially available systems which measure the impedance of body tissue by applying a current or voltage signal to the tissue and measuring the resulting voltage or current to determine the impedance of the tissues. Such systems can be used to monitor fluid build-up within the lungs, measure blood flow, monitor heart functions and perform similar functions for medical research. All known commercially available systems apply a single frequency signal to make the impedance measurements.

There is a need for a bio-impedance measuring system which is capable of making measurements at any frequency within a range of frequencies to permit the study of electrical impedances of intracellular and extracellular fluid composition. Such measurements are crucial for determining total body fluid in an intensive care unit, for dialysis, for physical fitness evaluations (body fat), and similar applications. Problems encountered in developing multiple frequency bio-impedance measurement systems include the difficulty of maintaining low intensity constant drive current through body tissue loads, and the ability to make consistent and accurate determinations of resistive and reactive impedance components at varying loads and different frequencies. Body analysis can be performed in different ways i.e segmental analysis and whole body analysis. In the whole body analysis the bioimpedance is calculated for the entire body and in the segmental analysis, bioimpedance is calculated for specific parts of the body like the arm, trunk, legs, etc.
Furthermore, the current pathway in the tissues is different for the varied frequency. Thus, a multiple-frequency bioimpedance measuring system plays an important role in the electrical property characterization of tissues. The accuracy of a BIA device depends primarily on the number of frequencies at which measurements are taken. That is why the choice of instrument is so important[3].

II. MULTIFREQUENCY SIGNALS

Bioimpedance is analyzed at various frequencies like single frequency, multiple frequencies and multifrequency. But there are certain drawbacks of single-frequency like low level currents with single frequency are limited to pass through only the ECF whereas the current with multi-frequency are able to pass through ECF as well as ICF and therefore it is very useful in various clinical applications. At 50 kHz BIA, i.e. single frequency BIA is strictly speaking not measuring TBW but a weighted sum of extra-cellular water (ECW) and intra-cellular water (ICW). SF-BIA permits to estimate fat-free mass and TBW, but cannot determine differences in ICW. BIA results are based on a mixture theories and empirical equations. As with SF-BIA, MF-BIA uses empirical linear regression models but includes impedances at multiple frequencies. MF-BIA uses different frequencies (0, 1, 5, 50, 100, 200 to 500 kHz) to evaluate FFM, ICW, TBW and ECW. At frequencies below 5 kHz, and above 200 kHz, poor reproducibility has been noted, especially for the reactance at low frequencies[4].

III. MULTISINE AND BINARY MULTIFREQUENCY EXCITATION SIGNAL

For the fast measurement of impedance spectrum of human tissue, the excitation signals can be often used successfully[5,6]. Though the multisine signal is the basic solution for this purpose[7], it is technically quite complicated to generate and is not very effective in the available range. The spectrum of multifrequency excitation signals must cover the frequency range of interest in a suitable way. For bioimpedance measurement, equal magnitude of spectral components and logarithmic distribution of frequencies are required more often.

![Fig. 1 Measurement of the impedance spectrum $Z(j\omega)$ of a biological object.](image)

A. Multisine excitation.

The frequencies $f_1$ to $f_n$ of $n$ sine wave components in the multifrequency signal (see Equation (1)) should fit the frequency range and the scale used:

$$S_{exc}(t) = \sum_{i=1}^{n} A_i \sin(2\pi f_i + \phi_i) \quad (1)$$

Typically, the logarithmic frequency scale is used in impedance analysis. Frequency doubling in sequence (e.g. 1, 2, 4, 8, 16, 32, 64, 128 etc.) seems to be widely used. Typically, the choice of frequencies is free. But use of the prime factor spacing between frequencies is the most reasonable solution, if the impedance is nonlinear. In this case, it is important to know that the nonlinearities of the impedance to be measured cannot cause such higher harmonics, which can coincide with the excitation frequencies. Still, for demonstration purposes we use log spacing. While comparing efficiency of different excitation signals, their peak values are important since being limited to max $A = V_s /2$ in electronic devices:

$$\text{peak}\{S_{exc}\}(t) = \max A \quad (2)$$

In principal, the Crest factor of a single sine wave is 1.414, but for the binary square wave signal it is 1. Consider a multisine excitation signal with normalized peak value max $A = 1$, containing $n$ = 11 equal amplitude (Ai) sine wave components. For simplicity the initial phase of all the components are taken as random, distributed uniformly within the full range ($-\pi$ to $+\pi$).
Frequency of the components $f_i$ here are taken $f_i = 2^i$ in the sequence 1, 2, 4, 8, 16, 32, 64, 128, 256, 512 and 1024 kHz i.e. frequency doubling. Generally, the following approximate equation can be used for estimation of the RMS values of separate sine wave components in the spectrum of multisine signal:

$$\text{(RMS)}_i \approx \max A/\text{CF}. \left(\frac{n}{2}\right)^{1/2} \quad (3)$$

B. Binary multifrequency excitation

Binary value (+1 and -1) square wave excitation has always a unity value crest factor. However, not all the energy is contained in the wanted spectral lines, about 60 to 70% of the total RMS value is spread between the lines.

$$b_{\text{exc}}(t) = \text{sign} \sum_{i=1}^{n} A_i \cdot \sin(2\pi f_i + \phi_i) \quad (4)$$

The binary multifrequency signal formulated from the corresponding multisine waveform as the signum function of it is much more effective than the optimized multisine signal.

IV. MF-Using Network Analyzer

Network analyzer, the AD5934 is a high precision impedance converter system solution that combines an on-board frequency generator with a 12-bit, 250 kSPS, and analog-to-digital converter (ADC). The frequency generator allows an external complex impedance to be excited with a known frequency. The impedance of the response signal is sampled by the on-board ADC and a discrete Fourier transform (DFT) is processed by an on-board DSP engine. At each output frequency, the DFT algorithm returns a real (R) and imaginary (I) data-word. After calibration, the magnitude of the impedance and relative phase of the impedance at each frequency point along the sweep is easily calculated using the following two equations:

$$\text{Magnitude} = \sqrt{R^2 + I^2}$$

$$\text{Phase} = \tan^{-1}\left(\frac{I}{R}\right)$$

AD5934 can be used to inject a stimulus signal through body part via a disposable probe. Response signal is analyzed and the effective impedance of the cavity is classified. The AD5934 is epitome for this application because it allows the user to tune to the specific frequency required for each test [8].

From the network analyzer data is given to microcontroller where coding is done for implementation on PC. PC application is written in Visual Basic. Microcontroller side coding is done using Embedded C. User selects START operation on PC. A command is sent to microcontroller over RS232 using serial port. Once the command is received, the microcontroller will start communication with AD5934 network analyzer. Microcontroller will set the initial frequency, final frequency and steps for increment and send start. The communication between microcontroller and network analyzer is done over I2C protocol. I2C performs chip-to-chip communications using only two wires in a serial interface. The two wires in the I2C Bus are called Serial Clock (SCL) and Data (SDA). These two wires carry addresses, selection, control, and data, one bit at a time. The serial data wire carries the data, while the serial clock wire synchronizes the sender and receiver during the transfer. The I2C bus can perform the same function as their larger parallel interface counterparts, but with far fewer pins.
This greatly reduces the size and cost of ICs based on the I2C bus. Once the sweep is complete, the microcontroller will read the values (real and imaginary) from registers and send it to PC one by one. On PC, the received values will be stored in files (patient records) and a graph will be plotted for analysis. User can load multiple graphs (ones stored earlier) to analyze the dielectric material under test (tissue /metal etc.) In this methodology multi-frequency bioimpedance measuring system provides good performance over the frequency range up to 100 KHz as well as the extensible system architecture [9].

V. BODY ANALYSIS

For body analysis we need a pair of electrodes i.e incentive electrodes and detection electrodes. The incentive electrodes pass the current into the body while the detection electrodes sense the voltage from the body. We can use a bipolar, tetra polar, and so on, sets of electrodes. We use these tetra polar electrodes for segmental analysis for more precision[10]. Body analysis can be performed in two ways whole body analysis and segmental analysis.

A. Whole-body Analysis

Most BIA models employ a so-called whole-body approach in which the body is modeled as a single cylinder and electrodes are placed at the wrist and ankle of one side of the body as shown in Fig. 3(a) and 3(b). This electrode configuration is referred to as distal bioimpedance measurement.

Consistency and standardization are the reasons for usually considering measurements of the right side of the body as the norm.

B. Segmental Analysis

Segmental-BIA requires initial standardization, specifically when different approaches and different BIA devices are employed.
Standardization of the type of electrodes used and their placement is a major concern. Segmental-BIA has been used to determine fluid distribution and fluid shifts in some diseases and may provide information on fluid accumulation in the pulmonary or abdominal region of the trunk. In the segmental analysis the body can be divided into five cylinders: two cylinders for legs, two for hands and a trunk. When we analyze the body according to these cylinders we can study the impedance of a specific region of the body. Fig. 5 shows a tetra polar electrode setup for different cylinders.

![Fig.5 Segmental analysis.](image)

VI. DISCUSSION

The binary multifrequency signal formed from the corresponding multisine waveform is more effective than the optimized multisine signal. We can analyze the human body using whole body and segmental analysis. For more precision multisegment body analysis can be performed.

REFERENCES

[8] AD5934 Application notes, Analog Devices Inc.