A Heart Rate Detection with Bio-impedance Signal Analysis using Impedance Analyzer

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Abstract: Electrocardiogram is the most widely used technique for heart rate measurement. ECG analysis can predict heart rate as well as physiological conditions of heart. In the project, the bioimpedance technique is explored to detect heart rate. It is a non-invasive technique comprises of impedance converter AD5933 which separates impedance into real and imaginary part. AD5933 has inbuilt I2C interface which is interfaced with ARM Cortex. Real and Imaginary part of bioimpedance signal are processed through mathematical formulation to determine value of bioimpedance. The bioimpedance data are collected on hyperterminal. An ECG and bioimpedance signal are plotted and compared with the help of matlab implementing QRS detection algorithm. Four electrodes are used for measurement of bio-impedance signal; two electrodes for injecting current and the other two to capture the voltage signal from human body. Electrodes connected to AD5933 are used as an interface to the human body for injecting current into the human body.

Keywords: Bio-impedance, DFT, impedance analyzer, I2C interface, heart rate, synchronization.

Introduction

When electric current is passed through human body, Human blood manifest change in its resistivity as well as its volume. Blood volume change and blood resistivity change result in change impedance. This electrical impedance possessed from human tissues is called bio-impedance. The opposition offered by human body to the current flowing through it is bio-impedance. This paper presents bio-impedance analysis carried out to detect heart rate. The heart beat occurrence is the result of systole and diastole activity of heart. During systole, the left ventricle accelerates a volume of blood through the ascending aorta and during diastole the ejected blood volume accelerates through the descending aorta due to its compliance. These kind of volume changes in blood during systole and diastole result in variations in bio-impedance. Thus, bio-impedance variations can be detected and processed to build a signal used to detect number of heart beats in specific time.

Literature Survey

Analysis of electrocardiogram signal is one of the established techniques for detection of heart rate. There are different methods for ECG signal detection and signal processes that are studied for the project. There are various instrumentation amplifiers and gain amplifiers studied for getting ECG signals and various signal processing algorithms are also taken into account. Savitzky-Golay filter is studied and its processing method for QRS detection is reviewed for ECG processing [3]. Bio-impedance is a technique used since 1948 in the field of biomedical research along with application development. Delia H. Diaz, Rafael Gonzalez-Landaeta, Oscar Casas and Ramon Paras Arney identified and developed Techniques to detect heart rate using single foot plantar electrode, plantar electrode and weighing machine using bio-impedance analysis [1, 4, 5].Four electrode method is used in these experiments although there are some variations in methods of connections. As synchronous demodulation is implemented in the experiments, extensive literature on synchronous demodulation and synchronous sampling is explored[2][8].The heart rate detection is carried out for a subject that stands on a common electronic weighing scale [5]. The method does not require any sensors attached to the body. The sensitivity and frequency response is evaluated for three different weighing scales and it is found that it is suitable for heart rate detection. A pulse detection system is also designed which can sense force variations about 240 mN. Similar experiments are carried out by Delia H. Diaz, Rafael Gonzalez-Landaeta, Oscar Casas and Ramon Paras Arney for single foot bioimpedance measurement and Plantar Aluminum electrodes. Blood acceleration in arota as well as systole-distole activity leads to variation in bioimpedance. This relation is used and proved in these heart rate detection method. There are methods to improve CMRR and signal-to-noise ratio [8].There are some studies which explore impedance analyzer AD5933 in bioimpedance techniques. As per requirement of project functioning and I2C interfacing of AD5933 is focused.

Measurement Principle

The systole and diastole activities lead to formation of distinguishable peaks in bio-impedance signal. It leads to considerable volume change in artery. This major change is represented by distinguishable peak in bio-impedance signal and QRS complex in ECG signal. The change in blood volume of the arteries and the change in the blood resistivity, both have contributions in impedance variations. The experiments and studies carried out relate the arterial volume change with impedance variations as follows:

$$\Delta V = -\rho \frac{L^2}{Z^2_0} (\Delta Z\rho + \Delta Zv) \qquad (1)$$

In equation (1) ΔV is the change in volume of arteries, L the length of artery section between the voltage electrodes, ρ the blood resistivity, and Z_0 the basal impedance of the non pulsatile tissues. $Z\rho$ is the impedance variations due to the blood resistivity change. Zv is the impedance variations due to the volume change [1].

For measuring bio-impedance, the carrier current of known amplitude and frequency is passed through human body using electrode and transmit stage of AD5933. The excitation signal is current. The carrier signal gets modulated due to impedance of human tissues and this modulated signal is due to bio-impedance. The bio-impedance signal can be detected at the output by using electrode. If current passed through human tissues is defined by equation (2)

$$i(t) = Icos(2\pi f_c t) \qquad (2)$$

and voltage measured for detected signal defined by equation (3)

$$v(t) = V(t) \cos\left(2\pi f_c t + \theta(t)\right) \qquad (3)$$

then the equation (3) can be written as equation (4) with $\theta(t)$ as delay occurred in detecting signal.

$$v(t) = V(t) \cos(\theta(t)) \cos(2\pi f_c t) - V(t) \sin\left(\theta(t)\right) \sin(2\pi f_c t) \qquad (4)$$

We can write resistance $R(t)$ as in equation (5).

$$R(t) = \frac{V(t)\cos(\theta(t))}{I} \qquad (5)$$

The reactance $X(t)$ can be written as in equation (6).

$$X(t) = \frac{V(t)\sin(\theta(t))}{I} \qquad (6)$$

Also $IR(t)$ and $IX(t)$ are in-phase and quadrature components of $v(t)$, respectively.
The impedance is calculated by using equation (7).

$$Z(t) = \frac{v(t)}{I} \qquad (7)$$

$R(t)$ and $X(t)$ are in-phase and quadrature component of $Z(t)$, respectively. In-phase component is resistive component comprising of real part of bio-impedance and quadrature component is reactive component comprising imaginary part of bio-impedance [2, 8].

To get the signal, four electrode bio-impedance measurement technique is used. This technique includes passing current through the body by employing two current injecting electrodes. It leads to variations in voltage due to impedance variations caused by changes in blood resistivity and blood volume. These variations are detected by two voltage measuring electrode. Bio-impedance signal will represent the variations in this voltage. Thus, arterial volume change as represented by bio-impedance signal is responsible for occurrence of heart beat.

Materials and Methods

In the novel method to measure heart rate, an attempt is made to use AD5933 for determining heart rate variations. The performance and possibilities of employing AD5933 in the heart rate determination system is explored in the project. In Figure 3, A indicates current injecting electrodes and B indicates voltage measuring electrodes. The excitation signal generated from AD5933 which is passed through human body and response signal is collected by AD5933 itself as shown in fig 3. AD5933 is interfaced with I2C Port of microcontroller ARM Cortex. The impedance values are calculated by ARM and stored in database using hyperterminal. The bioimpedance signal is build using the matlab.
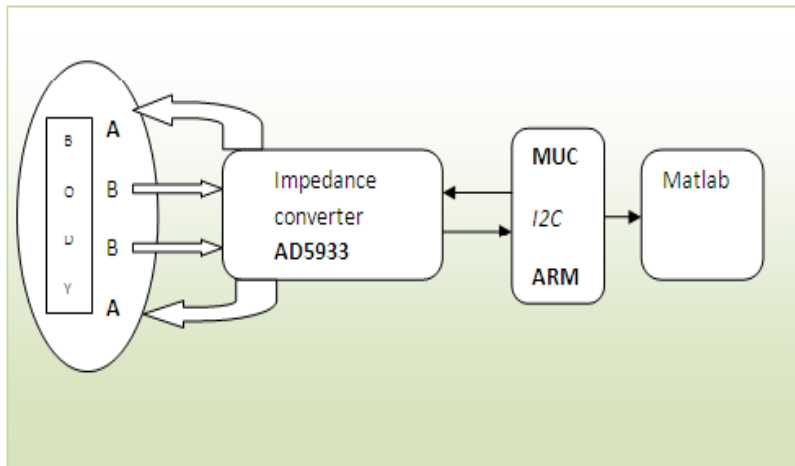
Fig 1: Measurement of heart rate using bio-impedance

A. Electrodes

Four ECG electrode measurement technique is for detecting the signal from heart beats variations. Four electrodes are interfaced with microcontroller to inject excitation signal as well as determine bioimpedance signal. Two electrodes are used for injecting the current. This current will vary due to impedance variations caused by arterial volume change. The output voltage generated due to current flow is measured by using another pair of electrode.

B. Signal Detector

Synchronous demodulation is used in detection of bio-impedance signal from current carrier. There are two methods for detecting signals. Out of these two methods, one method involves synchronous sampling by using AD630 demodulator which performs coherent demodulation [8]; while in another method sample and hold circuit is used for synchronous demodulation. Here, LTC 1043 and 1µF floating capacitor is used for realizing sample and hold circuit that yields high CMRR [2]. An attempt is made in this project to employ impedance converter AD 5933 to detect bioimpedance.

The AD5933 by Analog Devices is a high precision impedance converter system solution that combines an on-board frequency generator with a 12-bit, 1 MSPS, analog-to-digital converter. AD5933 is capable of generating excitation signal which can have maximum frequency of 100 KHz. The response signal from human body is sampled by on board ADC and a Discrete Fourier Transform is (DFT) processed by in built DSP engine. It has programmable frequency sweep capacity and serial I2C interface. It can measure impedance from 1KΩ to 10 MΩ. The AD5933 can accurately measure a range of impedance values to less than 0.5% of the correct impedance value with voltage supply of 2.7 V to 5.5 V.

Impedance conversion in AD5933 comprises three stages namely transmit and receive stages and discrete Fourier transform operation.

C. Transmit Stage of AD5933

As shown in Figure 2, transmit stage consists of direct digital synthesizer core that provides output excitation voltage of particular frequency. Waveforms from a single fixed frequency clock are created by direct digital synthesizer core. As shown in Figure 2, direct digital synthesizer core consist of 27-bit phase accumulator that provides excitation signal of particular frequency output. AD5933 permits the user to perform a frequency sweep. The user can decide the start frequency. The number of increments in frequency sweep and value of frequency increment can also be decided by the user.

Registers provided in the on board RAM are programmed using IDE (Integrated Development Environment) so as to define all three frequency sweep parameters i.e start frequency, number of increments in frequency sweep and value of frequency increment . The direct digital synthesizer output signal is passed through programmable gain stage to get the required peak-to-peak output excitation signal. This output excitation signal is passed through human body and the response signal detected using electrodes. The response signal from electrodes is fed to the receive stage. The range of output frequency, 1 KHz to 100 KHz, can be achieved with resolution with minimum value as 0.1 Hz.

D. Receive Stage of AD5933

In receive stage, current to voltage conversion takes place along with programmable gain. At this point, the impedance to be measured is unknown. The current developed across this unknown impedance flows into the V_{IN} pin of AD5933 and develops a voltage signal at the output of the current-to-voltage converter.
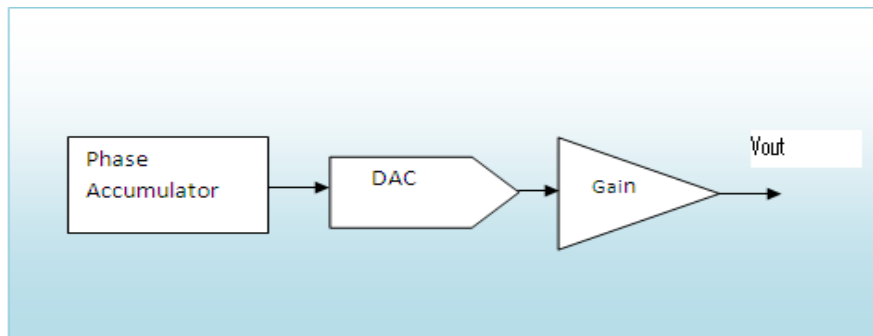
Fig 2: Transmit stage of AD5933

This voltage is amplified using programmable gain amplifier. Output signal from programmable gain amplifier is low pass filtered and given to 12 bit, 1MSPS analog-to-digital converter as shown in Figure 3. The control register in Ad5933 is programmed to control gain of programmable gain amplifier, output voltage of AD5933 and clock frequency. Control Register is designed so that it can control all the internal operation of AD5933 as well as communication with microcontroller.

E. Discrete Fourier Transform

Discrete Fourier transform can be used to approximate any signal as the sum of infinite sine and cosine functions. The results of discrete Fourier transform operation are complex numbers which comprise of real and imaginary part. Impedance is a complex number and hence AD5933 uses discrete Fourier transform for impedance conversion. In AD5933, discrete Fourier transform is calculated for each frequency point in the sweep. Equation (8) shows the calculation of discrete Fourier transform by AD5933.

$$X(f) = \sum_{n=0}^{1023} (x(n)(\cos(n) - j\sin(n))) \qquad (8)$$

In equation (8), $X(f)$ represents power in the signal at frequency point f, $x(n)$ the ADC output and $\cos(n)$ and $\sin(n)$ are the sampled test vectors provided by direct digital synthesizer core at frequency f.

The discrete Fourier transform returns a real and imaginary data word at each output frequency. These two values are stored in two separate registers of AD5933. After calibration the magnitude of the impedance and relative phase of the impedance at each frequency point along the sweep is easily calculated as in equation (9) and (10) respectively. This is done off chip using the real and imaginary register contents that can be read from the serial I2C interface [7].

$$Magnitude = \sqrt{R^2 + I^2} \qquad (9)$$

$$Phase = \tan^{-1}\left(\frac{I}{R}\right) \qquad (10)$$

Impedance Calculation

The real and imaginary part does not indicate the impedance value directly it has to go through mathematical calculations. The Gain Factor is a scaling factor required to determine impedance. The gain factor is calculated during the calibration of the system with known impedance connected between the VOUT and VIN pins. Once the gain factor is calculated, it can be used in the calculation of any unknown impedance between the VOUT and VIN pins.

A. Magnitude Calculation

The first step in impedance calculation for each frequency point is to calculate the magnitude of the DFT at that point. The DFT magnitude is given by

$$Magnitude = \sqrt{R^2 + I^2} \qquad (9)$$

where R is the real number stored at a specific register address in AD5933.
I is the imaginary number stored at a specific register address in AD5933.

B. Gain Factor Calculation:

$$Gain\ Factor = \frac{1}{\frac{impedance}{magnitude}} \qquad (11)$$

Where,

$impedance$ is the known impedance or calibration impedance connected between V_{in} and V_{out} pin. Generally 200 KΩ resistance is connected between these two pins.

$magnitude$ is obtained by inserting real and imaginary values in equation 9.These real and imaginary values are obtained for the calibration impedance connected between V_{in} and V_{out}.
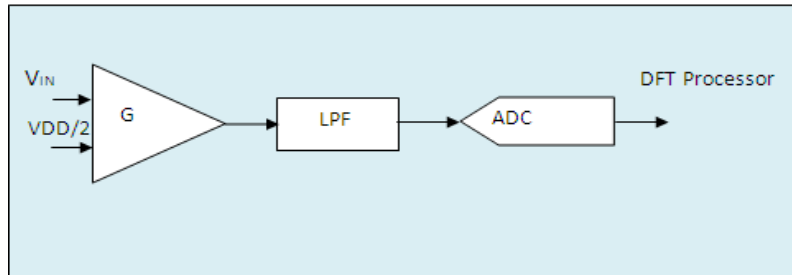

Fig 3. Receive stage of AD5933

E. **Impedance Calculation Using Gain Factor**

Final value of impedance for particular frequency sweep can be given by

$$impedance = \frac{1}{Gain\ Factor * magnitude} \qquad (12)$$

The $impedance$ values are determined by keeping VDD = 3.3 V, MCLK = 16.776 MHz, 2 V p-p output excitation voltage at the frequency 30 kHz.Also,200 kΩ is connected between Pin 5 and Pin 6 where as feedback resistor of 200 kΩ is connected between Pin 4 and Pin 5 i.e. V_{in} and V_{out}.

LPCXpresso is the integrated development environment used. It includes all the tools necessary to develop high quality embedded software applications in timely and cost effective fashion. It has device specific support for ARM cortex. LPCXpresso includes cortex microcontroller software interface standard libraries and source code.I2C interface program for interfacing AD5933 and Arm Cortex is developed in LPCXpresso environment.

The bio-impedance values are collected on hyper terminal with the help of flash magic. The signal is plotted and processed in matlab. The bioimpedance signal is compared with corresponding ECG signal. The ECG signal is detected using instrumentation amplifiers and it is interfaced with ADC of cortex. The analog signal is converted to digital one. These digital values are used to plot the signal in matlab.

Results and Discussion

The bio-impedance signal and ECG signal is plotted using peak detection algorithm. The results obtained are displayed as follows .With a exception or two the bioimpedance peak follows the ECG peak as shown in fig 4(a) (b). These graphs are executed in matlab using simple ECG electrodes. If more sensitive electrodes are used more precise results can be obtained. Heart rate can be estimated by applying threshold algorithm to bio-impedance signal. This results in train of pulses. Heart rate can be estimated by counting number of pulses during 10 seconds by using equation (11).

$$Heart\ Rate = Number\ of\ pulses\ in\ 10\ seconds \times 6 \qquad (13)$$

Conclusion

Impedance converter like AD5933 can provide real and imaginary components which gives bio-impedance values. Bio-impedance signal can be plotted and denoised using these values.ARM cortex processor can be effectively used to process the captured bio-impedance signal. The systole and diastole activity occurring periodically affects the bio-impedance signal. Bio-impedance signal shows clear upward and downward deflection with reference to systole and diastole activity. This results in measurement of heart rate. It must be noted that electrode and its position plays important role in signal detection. More sensitive electrode can be attached to different position of body to determine precise heart rate.
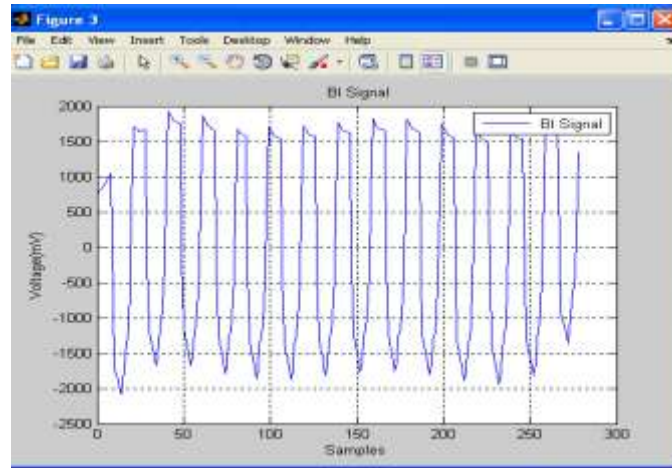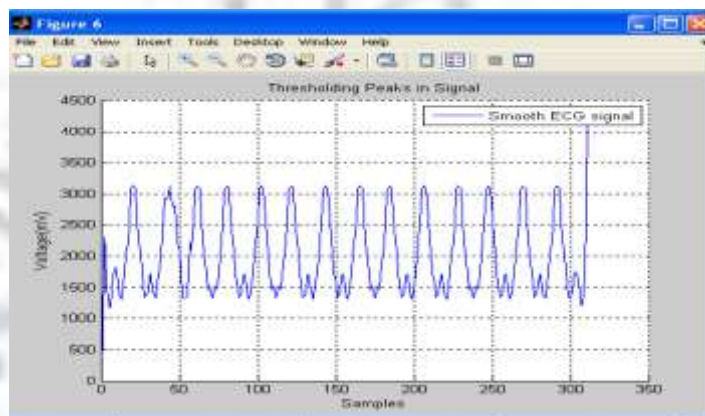
Fig 4(a). Bio-impedance Signal

Fig 4(b). ECG Signal

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