SPREAD SPECTRUM BIOIMPEDANCE MEASUREMENTS FOR REJECTING JAMMING SIGNAL

In-Duk Hwang and Hyun-Gak Kang

Department of Electronics Engineering, Daejeon University,

Yongwoon-Dong, Dong-Gu, Daejeon, 300-716, Korea

idhwang@dju.ac.kr

Abstract: When we measure impedance of a small object, such as an electronic component, external interference or jamming signal can be rejected by shielding the object. However, when we measure impedance of a human body, shielding is not easy and severe error due to the interference could be introduced. In this presentation, spread spectrum technique applicable to bioimpedance measurements for rejecting external interference without shielding is introduced.

Introduction

Bioimpedance analysis is a promising area with many applications [1-2]. However, when we measure impedance of a human body, external interference or jamming signal from various sources could be introduced resulting in severe error in the measurement. When we measure impedance of a small object, such as an electronic component, external interference can be rejected by shielding the object. However, shielding a human body is inconvenient. A medical device implanted into or worn on a human body can also be an interference source for bioimpedance measurement.

In modern wireless communication, spread spectrum (SS) technique is being used for rejecting external interference and enhancing bandwidth efficiency [3]. Because signal power radiated from a SS transmitter is spread broadly in frequency domain, interference effect on narrow band receivers in the adjacent channel can be mitigated. However, the SS technique has not been applied to bioimpedance measurements.

Thus, in this presentation, the SS technique is applied to bioimpedance measurement. SS bioimpedance measurement in this presentation has following advantages; 1) decreased measurement error due to interference generated from various external sources 2) decreased measurement error due to interference generated from implanted or worn devices (medical or general electronic devices), and 3) decreased interference on other surrounding or implanted medical devices due to bioimpedance measurement itself.

After implementing measuring circuit, we confirmed experimentally that SS bioimpedance measurement can increase signal to jamming ratio (SJR).

Theory

To measure bioimpedance, current is injected into human body and voltages induced by injected current are measured. Figure 1 shows the waveform of injected current. In conventional impedance measurement, the waveform of injected current is a continuous sinusoid. (Fig. 1. a)). In SS impedance measurement introduced in this presentation, the phase of injected current was changed by 180 degrees at the instant of the binary pseudo-noise (PN) sequence transition (Fig. 1. b)). Figure 1. b) shows an example in case that the PN sequence is 101101.... In this Figure, f_s and f_c represent measurement frequency and PN sequence rate, respectively. The duration of a single PN sequence value called a chip period was denoted as $1/f_c$.

Waveforms of voltages induced by injected current are similar to that of injected current, but changes in magnitude and phase will occur when the object is reactive. A block diagram for voltage detection in SS bioimpedance measurement introduced in this presentation is shown in Figure 2. The architecture itself is the same as that of the conventional or standard bioimpedance measurement. It is for a phase sensitive detector or a correlator. The difference is in that the input signal to be measured and the reference signals (I and Q signals) are spread. Because the reference signals are spread by the same PN sequence as that used for the input signal, the output signals of the multipliers are

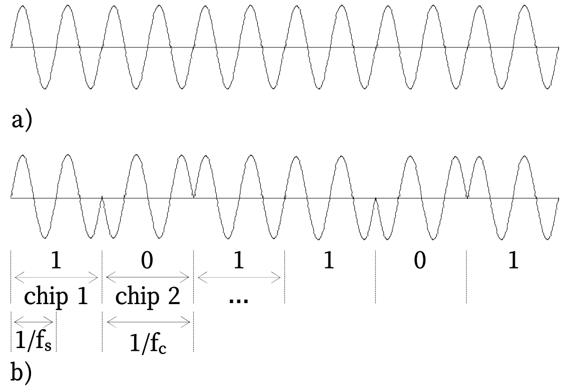

Figure 1: Waveforms a) in conventional and b) in spread spectrum impedance measurements

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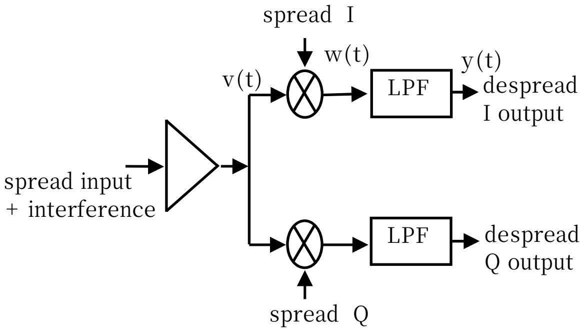


Figure 2: Block diagram of the detection system in spread spectrum mode.

despread. It is notable that the waveform in Fig. 1. b) and the block diagram in Fig. 2 are the same as those of BPSK (Binary Phase Shift Keying) modulation and demodulation scheme in digital communication.

To calculate signal-to-jamming ratio (SJR), a single-tone jamming signal was assumed. In conventional detection mode, input signal of the in-phase (I) multiplier is represented as

$$v_{con}(t) = \sqrt{2P_s}\cdot\cos(2\pi f_s t + \phi) + \sqrt{2P_j}\cdot\cos(2\pi f_j t) \quad (1)$$

where P_S, P_j, f_s, and f_j represent signal power, jamming power, signal frequency and jamming frequency, respectively. The input signal is multiplied by the reference signal (the I signal) $\sqrt{2P_I}\cdot\cos(2\pi f_S t)$. Then, the output signal of the in-phase (I) multiplier is

$$w_{con}(t) = \sqrt{P_s P_I}\cdot[\cos\phi + \cos(4\pi f_s t + \phi)] + \sqrt{P_j P_I}\cdot\{\cos[2\pi(f_j - f_s)t] + \cos[2\pi(f_j + f_s)t]\} \quad (2)$$

When the transfer function of the low pass filter is

$$H(f) = \frac{1}{\sqrt{1+\left(\frac{f}{f_o}\right)^2}} e^{-j\theta} \quad (3)$$

where $\theta = \tan^{-1}\left(\frac{f}{f_o}\right)$ and f_O is the low pass filter cutoff frequency, the output signal is

$$y_{con}(t) = \sqrt{P_s P_I}\cdot\cos\phi + \sqrt{\frac{P_j P_I}{1+\left(\frac{f_j - f_s}{f_o}\right)^2}}\cdot\cos[2\pi(f_j - f_s)t - \theta] \quad (4)$$

Output power is obtained as

$$Y_{con} = P_s P_I\cdot\cos^2\phi + \frac{P_j P_I}{2\left[1+\left(\frac{f_j - f_s}{f_o}\right)^2\right]} \quad (5)$$

The first term is the signal power and the second one is the jamming one. Thus, the signal-to-jamming ratio (SJR) for the conventional mode is

$$SJR_{con} = 2\frac{P_s\cdot\cos^2\phi}{P_j}\cdot\left[1+\left(\frac{f_j - f_s}{f_o}\right)^2\right] \quad (6)$$

The SJR can be approximated as below

$$SJR_{conv} \approx 2\frac{P_s\cdot\cos^2\phi}{P_j}\cdot\left(\frac{f_j - f_s}{f_o}\right)^2 \quad (7)$$

for $f_0 << f_j - f_s$.

In the SS mode, the input signal of I-multiplier is

$$v_{ss}(t) = \sqrt{2P_s}\cdot c(t)\cdot\cos(2\pi f_s t + \phi) + \sqrt{2P_j}\cdot\cos(2\pi f_j t) \quad (8)$$

PN code waveform c(t) can take +1 or -1. After being multplied by spread I signal $\sqrt{2P_I}\cdot c(t)\cdot\cos(2\pi f_s t)$, the signal term in eq. (8) is despread while the jamming term is spread. Thus, output of the multiplier is

$$w_{ss}(t) = \sqrt{P_s P_I}\cdot[\cos\phi + \cos(4\pi f_s t + \phi)] + \sqrt{P_j P_I}\cdot c(t)\cdot\{\cos[2\pi(f_j - f_s)t] + \cos[2\pi(f_j + f_s)t]\} \quad (9)$$

If we assume the PN sequence is long, the power spectral density of the output is continuous and is given by

$$W_{ss}(f) = P_s P_I\cdot\cos^2\phi\cdot\delta(f) + \frac{P_j P_I}{4 f_c}\cdot\left\{\sin c^2\left[\frac{f-(f_j - f_s)}{f_c}\right] + \sin c^2\left[\frac{f+(f_j - f_s)}{f_c}\right]\right\} \quad (10)$$

The low pass filter passes whole portion of the signal power, but passes partial portion of the jamming power in the passband. When $f_o << f_c$, the output power of the low pass filter is

$$Y_{ss} = P_s P_I\cdot\cos^2\phi + \frac{P_j P_I}{f_c} f_o \quad (11)$$

The first term is the signal power and the second one is the jamming one. The resulting SJR for the SS mode is

$$SJR_{ss} = \frac{P_s\cdot\cos^2\phi}{P_j}\cdot\frac{f_c}{f_o} \quad (12)$$

Thus improvement in SJR by the SS technique is

$$\frac{SJR_{ss}}{SJR_{conv}} = \frac{f_c}{2 f_o\left[1+\left(\frac{f_j - f_s}{f_o}\right)^2\right]} \quad (13)$$

and

$$\frac{SJR_{ss}}{SJR_{conv}} \approx \frac{f_c f_o}{2(f_j - f_s)^2} \quad (14)$$

for $f_0 << f_j - f_s$.

Implementation

Block diagram of the whole system implemented and used to demonstrate SS bioimpedance measurement is shown in Figure 3. The whole system is controlled by a microprocessor (80c196kc). The waveforms for the SS mode or the standard mode were synthesized using the commercial direct digital frequency synthesizer chip (AD9854) which has 48-bit frequency resolution and provides quadrature output. The voltage follower receives the I-signal from the synthesizer and injects current into the object. The vector phase sensitive detector was implemented using high-speed analog multiplier chips and operational amplifiers. The vector phase sensitive detector receives the I- and Q-signals from the frequency synthesizer and uses them as a reference. Thus, as described ealrier, despreading can be done with a conventional phase sensitive detector circuit. The 16-bit analog-to-digital converter (ADS8322) converts the multiplexed I- and Q-outputs after receiving the sampling request signal from the microprocessor. The microprocessor accumulates the converted data and dumps it to PC through a serial communication. The data is analyzed in the PC.

The whole system can be operated in the SS mode or the standard mode according to the microprocessor program controlling the frequency synthesizer. In the SS mode, a PN sequence of length N=31 was used. The phases of the I- and Q-signals generated at the frequency synthesizer become 0 and 180 degrees simultaneously according to the code value of 0 and 1, respectively.

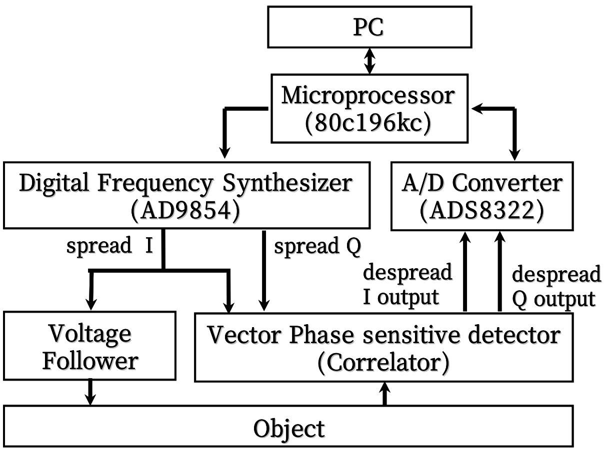


Figure 3: Block diagram of the whole impedance measurement system

Experiments and Results

To examine the ability to reject external interference of the implemented system, impedance measurement was done while intentional interference was applied. As an object to be measured, a simple 1 kΩ resistor was used to clarify the experiment. The measurement frequency and the peak-to-peak applied voltage to inject current to the object were 74 kHz and 28 mV, respectively. The chip-rate was 37 kHz. The sample rate of the ADC and the cut-off frequency of the first order low pass filter were 37 kHz and 100 Hz, respectively. The frequency and the peak-to-peak voltage of the intentional interference were 74.5 kHz and 7 mV, respectively. Thus, SJR at the resistor was 12 dB.

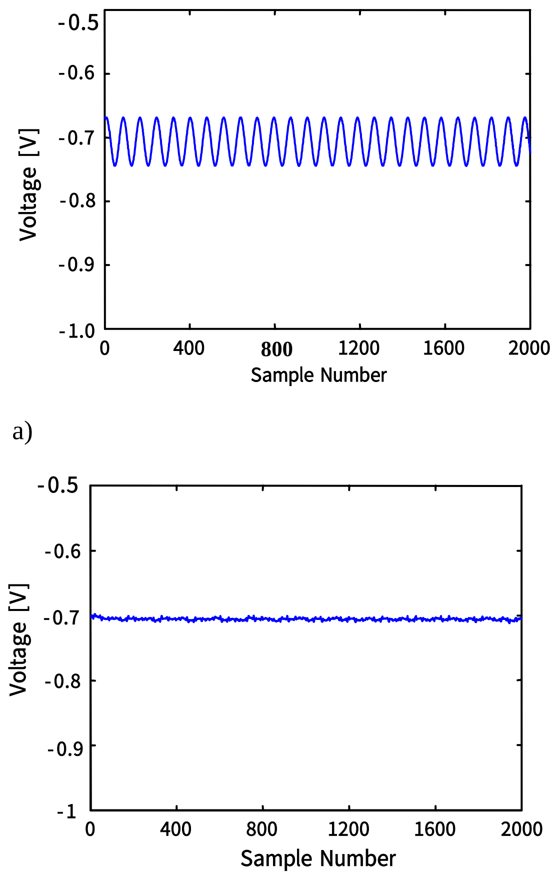
Figure 4 shows the output voltage of the AD converter. The 'sample number' of the horizontal axis multiplied by sampling period is the sampling instant. Sampling is done after steady state is reached. The output voltage measured in the conventional mode is shown in Fig. 4. a). In the Figure, we can see the measured voltage oscillates. Thus, there can be an error in the measured voltage up to the peak-to-peak voltage of the oscillation according to when the sampling is done. The signal power and jamming power were calculated as

$$P_s = \bar{v}_n^{\,2} \quad \text{and}$$

$$P_j = \frac{\sum_{n=0}^{N-1} \{v_n - \bar{v}_n\}^2}{N}$$

where $\bar{v}_n$ and v_n are the average voltage and the voltage sampled at the n-th sample number, respectively. The SJR is 28.5 dB.

Figure 6. b) shows the output voltage measured in SS mode. There is no oscillation which means higher SJR. The SJR was 51.5 dB. Thus, when the jamming frequency (74.5 kHz) is 500 Hz apart from the signal frequency (74.0 kHz), 23 dB improvement in SJR was achieved.



a)

b)

Figure 4: Output voltages measured a) in conventional mode, and b) in SS mode (f_j =74.5 kHz, f_s =74 kHz, f_o =100 Hz, and f_c =37 kHz)

SJR improvement ($SJR_{ss} - SJR_{con}$) was obtained while the jamming frequency was varied. The result is summarized in Table 1. As the jamming frequency approaches the measurement frequency, the SJR in the conventional mode was degraded severely. However, the SJR in the SS mode was maintained at a high level. This means that the SS bioimpedance measurement is very effective for rejecting jamming signal. The improvement in Table 1 is better than expected from eq. (13). This is because, whereas we assumed the power spectral density of the jamming signal at the output terminal of the multiplier is continuous in eq. (10), the actual power spectral density is discrete and the DC term of it is small since the PN sequence has a period of N/ f_c .

Table 1: Jamming frequency and SJR improvement (f_s =74 kHz, f_o =100 Hz, and f_c =37 kHz)

f_j (kHz)	SJR_{ss} (dB)	SJR_{con} (dB)	$SJR_{ss} - SJR_{con}$ (dB)
74.1	46.1	17.7	28.4
74.2	48.8	21.5	27.3
74.5	51.5	28.5	23.0
75.0	50.3	34.5	15.8
76.0	46.1	40.8	5.3
78.0	36.4	48.1	-11.7

From Table 1, we can see that as the jamming frequency goes away from the measurement frequency, the SJR improvement is degraded. This is because the jamming signal is attenuated at the low pass filter, which improves SJR in the conventional mode. This does not mean that the conventional measurement is better than the SS measurement when the jamming frequency is far away from the measurement frequency. It is remarkable that the difficulty in rejecting jamming signal remains tough only when the jamming signal is near the measurement frequency. When the jamming signal is far apart from the measurement frequency, the jamming signal can also be reduced by various analog and digital signal processing technique. In addition, it is expected that we can get better SJR improvement if we choose higher cut-off frequency for a low pass filter according to eq. (14).

Conclusions

Spread spectrum technique was introduced for rejecting interference during bioimpedance measurement. SS bioimpedance measurement in this presentation has following advantages; 1) decreased measurement error due to interference generated from various external sources 2) decreased measurement error due to interference generated from implanted or worn devices (medical or general electronic devices), and 3) decreased interference on other surrounding or implanted medical devices due to bioimpedance measurement itself.

The improvement in signal-to-jamming ratio by the SS technique was experimentally confirmed.

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