# A Design of Rheoencephalography Acquisition System Based on Bioimpedance Measurement as the Basis for Assessment of Cerebral Circulation

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*Received: September 07, 2018; Accepted: November 26, 2018*

**Abstract**

*To evaluate human's cerebral blood flow (CBF), electrical rheoencephalography (REG) is one of the most notable electrophysiological technique, which has been investigated for a long period. This technique non-invasively measures the electrical impedance of the cranial cavity region through scalp electrodes reflecting the changes in brain's conductivity due to blood circulation during cardiac cycles. This paper aims to present a design of low-cost system able to continuously record rheoencephalography signal using bioimpedance method. This REG system comprises of main components such as: voltage-controlled current source (VCCS), signal recorder, AM demodulator, analog-to-digital converter, digital signal processor, and signal displayer. This design has a prominent feature that allows to measure the signal without requiring of high resolution ADC (usually 24 bit) and utilizes the simple envelop detecting circuit for AM demodulator. The high-frequency VCCS in the design is also thoroughly designed to ensure the quality of recording signal. The design is implemented, and then is evaluated on simple RC series model for static impedance and standard bio-impedance simulation device (with two kind of waveforms) for dynamic impedance. The results show the high correlation between the standard and recorded signals: R2 is 0.9815 for RC series model; RMSE and rRMSE for waveform 1 are 17.14 and 0.0857%; RMSE and rRMSE for waveform 2 are 13.58 and 0.0679% correspondingly.*

Keywords: Rheoencephalography (REG), Cerebral Blood Flow (CBF), AM demodulator, Analog-to-digital converter (ADC), Howland Current Pump

## 1. Introduction

To ensure that the brain functions normally, it is required to maintain an adequate cerebral blood flow (CBF). The normal blood flow for entire brain is 750 to 900 ml/min that accounts for 15 per cent of the resting cardiac output. It is pointed out that cerebral blood flow and metabolism of the brain tissue have a strong relationship like other vascular areas of the body. Cerebral blood flow can be affected by at least three metabolic factors: (1) carbon dioxide concentration, (2) hydrogen ion concentration, and (3) oxygen concentration [1]. Especially in case of head injuries, to select an adequate therapy for patients as well as observe its effect on them, CBF monitoring in real time plays an important role. In reality, continuously monitoring CBF of patients at bedside would be greatly attractive in clinical practice [2].

Rheoencephalography (REG) was first presented by Polzer and Schugfried in 1950 [3]. This technique is a branch of the impedance plethysmography that is specially applied to the head. People use this approach to indirectly measure the cerebral blood volume during each cardiac cycle based on the variation of head impedance. It is derived from the fact that brain tissue and blood have the different electrical conductivities, hence the head impedance reflects the impedance ratio of these two components [4]. However, the amount of brain tissue is minor (0.4-0.8%) [5] and hance can be supposed to be unchanged in a short stage of human's development. Therefore, the variation of head impedance is due to the blood flow circulating in head. To record these changes, the authors [3, 6, 7, 8] applied an alternating current to the head through electrodes attached on the skin of patient's head with the frequency range of 20-140 kHz, amplitude of current is about 2mA. Because of its outstanding features like non-invasiveness, simplicity, cost-effectiveness and ability to measure continuously, REG has been greatly attractive in clinical practice.

Among electrode configuration proposed by some authors [9, 10], the most frequently used one in measuring rheoencephalography are: REG I and REG

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II. The REG I is bipolar configuration, while the REG II is tetrapolar one. In bipolar configuration, the injecting current and sensing voltage are conducted on the same set of electrodes (2 electrodes) attached on patient's skin. In the meanwhile, the tetrapolar configuration uses two separated couple of electrodes to execute these two functions. REG II is preferred to REG I because it overcomes the drawback of REG configuration that is the mismatch between skin-electrode impedance, cable impedance, etc. leading to error in measuring the waveform.

Since its appearance, REG has been a controversial technique because of REG signal's contamination, which is the result of extracranial circulation. For safety reason, the current injected to the head through electrodes attached on head surface has to be low intensity. However, because of low conductivity of skull compared to scalp and brain tissues, the current injected to the head is mostly trapped in the scalp instead of penetrating skull to reach brain tissue. Hence, the source of recorded REG signal derives from the pulsatility of blood volume in scalp instead of cerebral blood flow. Nevertheless, Perez et al. [11] have pointed out that existing an arrangement of electrodes in REG II which minimizes the impact of extracranial impedance changes in sense of theory. Using finite element method in combination with four-shell spherical model of the head, the other authors have proved this hypothesis [12, 13].

This paper concentrates on designing a low-cost system able to acquire, display, and store REG waveform using bio-impedance method as the base for researching about characteristics of REG waveform supporting diagnosis and assessment of cerebral circulation instead of analyzing about the capability of REG to calculate CBF. In proposed REG acquisition system, a low intensity, high-frequency sine wave current is injected to the head between two electrodes and the sensed voltage is received through two other electrodes (pickup electrodes).The recorded impedance information consists of a base component, Z0, and a variable component, ΔZ. The system comprises of sub-circuits used to receive, process and transmit signals to the computer for display and storage that facilitates teaching, researching, and diagnosis. All the circuits are carefully considered, designed, and tested to ensure the reliability that the system offers.

## 2. System Design

Based on the measuring principle and design considerations, we conducted designing a REG system that has capability of recording the rheoencephalography signal and transmit to the computer for display and storing. The block diagram of the REG system is illustrated as the Fig. 1.

According to the designed diagram, the system consists of three following main blocks: (1) Current generator, (2) Analog signal recording and processing unit, (3) Digital signal processing unit.

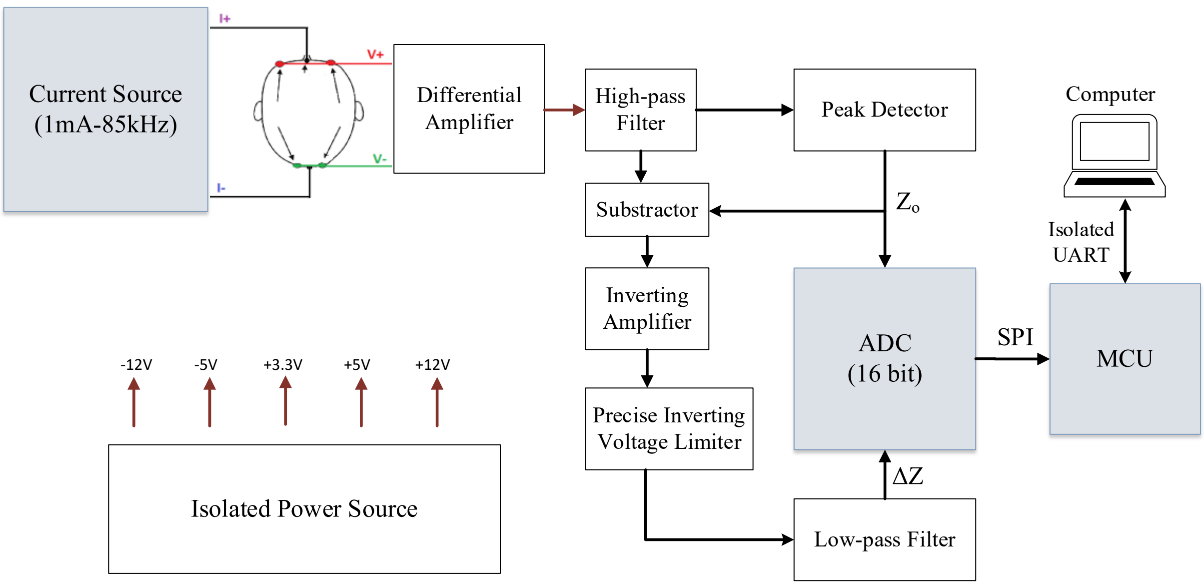


**Fig. 1.** Block diagram of the proposed acquisition system for REG signal

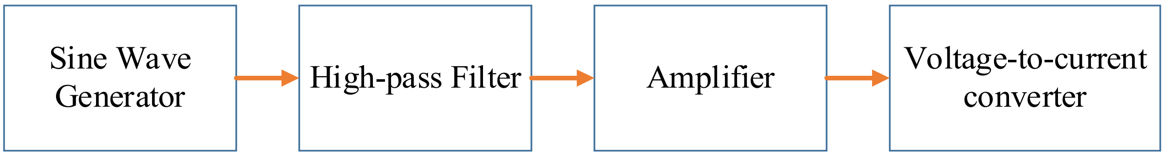


**Fig. 2.** Block diagram of the current source generator

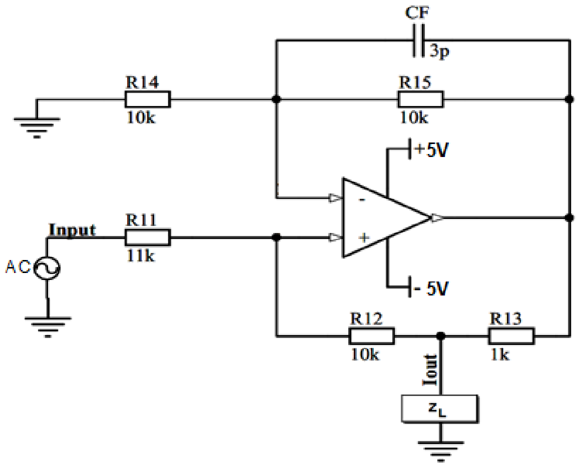


**Fig. 3.** Improved Howland Current Pump Topology

### *2.1. Current Generator*

Considering the patient safety and quality of the achieved signal (signal-to-noise ratio), the parameters of excitation unit were selected as frequency of 85 kHz and amplitude of 1mA. The frequency is selected as according to the common range of 50 kHz – 200 kHz for REG [14]. The stimulating current amplitude of 1 mA that is safe enough for bioimpedance measuring but not too weak to ensure piercing ability through the scalp to reach the brain.

The type of current source used in this design is voltage-controlled current source (VCCS). This current source is capable to generate AC constant current to the object with an adjustable amplitude of 10uA to 5mA and programmable frequency of 100 Hz to 400 kHz. The block diagram of the current source generator is designed as illustrated in Fig. 2.

*Current generator:* To generate high frequency sine-wave voltage, AD9833 (Analog Device) is used in this design. This waveform generator IC is controlled by the microcontroller TM4C123GH6PM (Texas Instruments) through Serial Peripheral Interface (SPI) protocol.

*High-pass filter:* The sine–wave from AD9833 always has the DC offset because the IC uses the single supply. However, to ensure the safety for patients the DC component of the current source must be canceled. Hence, before applying the sine–wave from AD9833 to the input of the Voltage–to–current converter, a high-pass filter is essential to eliminate the DC component. A simple active 1$^{st}$ order high-pass filter is used to implement this. The corner frequency is selected to be 10 Hz to remove DC component and not effect to the high-frequency component.

*Amplifier:* In addition, for purpose of adjusting the amplitude of the current source, an inverting amplifier is added to adjust the amplitude of the sine–wave, hence adjust the amplitude of the AC current source. OPA2211 (Texas Instruments) is selected to perform this task due to its prominent features like low noise density, low voltage and low current noise, high speed.

*Voltage-to-current converter:* The Improved Howland Current Pump Topology is selected for Voltage-Current Converter for reason of ability to provide bi-polar output current, wide frequency range, high output impedance, temperature stability due to using op-amp.The condition for current balance is:

$$\frac{R_{11}}{(R_{12}+R_{13})} = \frac{R_{14}}{R_{15}} \tag{1}$$

The output current is calculated as:

$$I_L = V_{In} \times \frac{R_{12}}{R_{12}+R_{11}} \times \left(\frac{1}{R_{12}} + \frac{1}{R_{13}} + \frac{R_{15}}{R_{13}R_{14}}\right) \tag{2}$$

With the condition $R_{14} = R_{15}$, and $R_{11} = R_{12} + R_{13}$, the output current is simply calculated as:

$$I_L = \frac{V_{in}}{R_{13}} \tag{3}$$

However, this topology has one drawback that is the requirement of very precise resistor to match the ratio and op-amp with high open loop gain as well as high CMNR to achieve a high output impedance current source especially at high frequency waveform. Because in bioimpedance measurements, the current source directly affects the quality of recorded signal, the authors took a careful consideration in PCB layout, selecting precise resistors (0.1% tolerance) and selecting the op-amp (OPA2211 is used for reason of prominent features mentioned above) to ensure the quality of the current source.

### *2.2. Analog signal recording and processing unit*

In most cases, the sensed voltage from electrodes has some characteristics like low amplitude due to the common range of impedance pulse in REG is from 0.10 to 0.25 Ω [15] as well as low intensity of the excitation current (1 mA), high frequency (85 kHz). A preamplifier is essential for further processing. A good preamplifier plays extremely important role directly related to signal quality. The system is required of recording variable component as well as base component, hence it demands excellent features at both of ac and dc performance. To execute this task, the instrumentation amplifier IC AD8421 (from Analog Devices) is selected due to its great features like high slew rate 35V/µs, high common mode rejection rate 94 dB (G=1), low voltage noise density 3.2 nV/√Hz at 1 kHz, and low offset voltage drift 0.2 µV/oC that is suitable for handling this kind of signal [16]. This IC also converts the differential signal to single-ended type that is more suitable for processing.

To eliminate any DC offset components derived from the contact between body and electrodes as well as the ECG signal coupling to electrodes, a high-pass filter with corner frequency of 1 kHz is used. The filter type selected is 2nd-order Butterworth active filter to ensure the maximal flatness and phase linearity according to Sallen-Key topology. The downside about the roll-off slope of this filter is overcome by selecting the cutoff frequency of 1 kHz that is far from the demodulated signal bandwidth of about 85 kHz.

The signal is then fed into an AM demodulator to extract both variable and base impedance from the carrier. The variable impedance that reflects the blood circulation in head is 0.10 to 0.25 Ω [15], relative small compared to the base impedance that can be up to 200 Ω [17]. This unchanged component often limits the gain of the amplifier; therefore, it requires the measuring system with high bit ADC (24 bit) to ensure the resolution of the signal. The 24-bit ADCs often have drawbacks involving interference of noises, limitation in sampling rate, and processing speed due to the large number of data bits. With some adjustments in combination with the simple envelop detector, the system overcomes this challenge and offers ability to record signal with good resolution just using 16 bit ADC. To utilize the simple envelop detecting circuit, the signal should be amplified more without saturating the output. To implement this idea, the DC component should be suppressed by a subtractor; however, the base impedance is not identical for every patients. Hence, subtracting a certain amount of DC component is not suitable in this case. To handle this issue, our AM demodulator proposed to use an extra peak detector to actively get the signal belonging to the base impedance. Furthermore, a variable resistor is also added to adjust the percent of DC component fed to the subtractor. The schematic of the peak detecting circuit is illustrated as in Fig. 4.

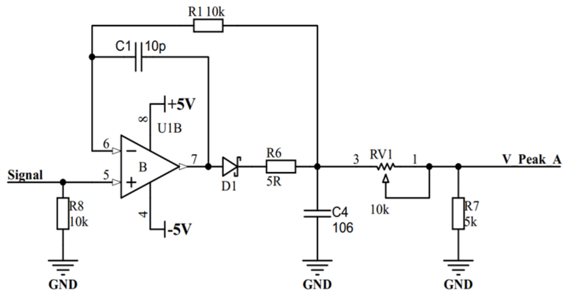


**Fig. 4.** Peak detecting circuit schematic diagram

To perform the subtracting function, the integrated difference amplifier INA133 (from Texas Instruments) is selected to use instead of using the subtractor built from discrete components including resistors and general purpose op-amp to ensure stability and precision of the circuit. INA133 is a high-speed (slew rate of 5V/ µs), precision difference amplifier (consisting of a precision op-amp with a precision resistor network) [18] that fulfills the technical requirements of the system. Based on the percent of DC component fed to the subtractor, the amplification gain is selected appropriately (usually selected gain is 10). With a reasonable gain, the signal is then magnified by an inverting-amplifier without saturating the output.

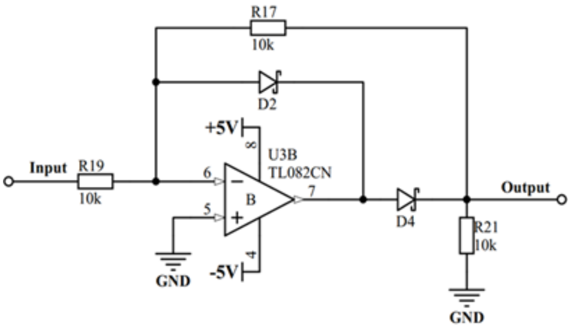


**Fig. 5.** Inverting voltage limiter schematic diagram

To extract the REG signal, the envelop detector is used for AM demodulating because of its simplicity, separation from the influence of the phase shift of the current when it goes through the body. The envelop detector comprises of a precise inverting voltage limiter and a $2^{nd}$ order low-pass filter. For envelop detector, only one side (negative or positive) of signal is necessary for demodulating. Therefore, the signal is passed through a precise inverting voltage limiter (or inverting half-wave rectifier) before entering the low-pass filter. The inverting voltage limiter has function to invert the signal and then eliminate the negative part and maintain only the positive part. The schematic of the inverting voltage limiter is illustrated as in Fig. 5.

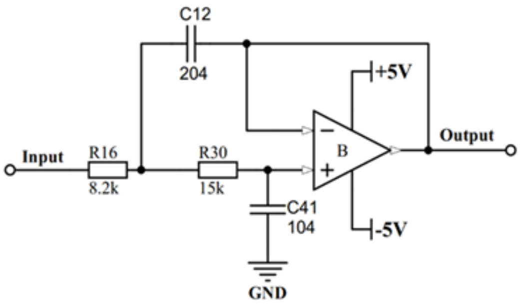


**Fig. 6.** Low-pass filter circuit schematic diagram

To accomplish the demodulation of the signal, a 2nd order Butterworth low-pass filter is used to attain the low frequency component, that is the REG component, and suppress the high frequency components including carrier and noise. The type of the filter is Butterworth, and the topology is Sallen-Key that is still the same as the filter used upon. The cutoff frequency is selected as 150 Hz that is enough to eliminate the high frequency components without attenuating the wanted signal. The schematic of the low-pass filter is illustrated as in Fig. 6.

### *2.3. Digital signal processing unit*

Both signals according to base impedance and variable impedance are digitized simultaneously using the external ADC IC ADS1120 (from Texas Instruments) with the sampling rate of 200 samples/sec. This ADC has some features like 16-bit resolution with internal 2.048V reference, on-chip programmable gain amplifier with gain from 1 to 128, four single-ended input channels, and programmable data rate up to 2 ksps [19]. According to the set of parameters using 2 single-ended channels, sampling rate of 500 samples/sec for each channels, amplification gain of 1, the ADC can measure the signal with voltage resolution is 0.03125 mV in the range from GND to 2.048V. The microcontroller can communicate with the ADC though SPI protocol.

The two streams of data are fed to additional digital filters to remove any unwanted noise from PCB traces, power source, and ADC sampling transients before transmitting to the computer. The designed filter is the digital IIR (Infinite Impulse Response) low-pass filter developed through bilinear transformation based on the analog Butterworth filter. This IIR filter type reduces the computation time because it requires low order filter to implement, hence, suitable for microcontroller platform. Through bilinear transformation, the balance of roll-off slope and phase distortion characteristic of analog Butterworth filter is transfer to the digital filter. The setup parameters of the filter are: Fpass = 100 Hz, Fstop = 200 Hz, Apass = 1 dB, Astop = 40 dB (F denotes for frequency, A denotes for attenuation); the filter order is 4.

The two digitally filtered streams of data is then transfered to the computer through UART protocol with the baudrate of 115200 to ensure the speed of transmission as well as the reliability of the signal. The two signals are displayed simutaneously on the screen offering ability to monitor the waveform of signals in real-time as well as store data in format of .csv file for further processing. However, for safety reason of the patient during measurement, the computer and the acquisition system should be digitally isolated. ISO7421 from Texas Instruments was selected to ensure the high data transfer rate (baud rate is about 115200 or even more), stability, and safety. The ISO7421 provides galvanic isolation up to 2500 VRMS for 1 minute per UL, signaling rate 1Mbps, two isolated channels that meets the requirements of the system [20].

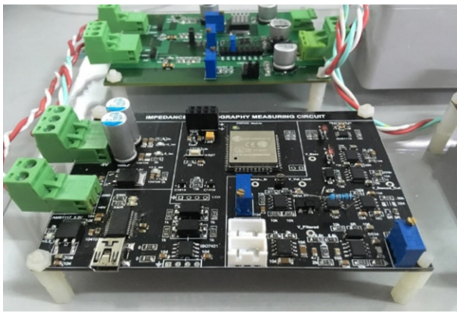

**Fig. 7.a.** The implemented REG signal acquisition circuit

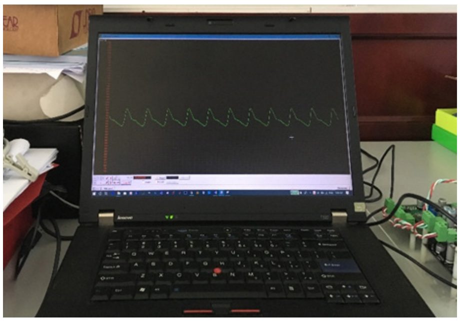

**Fig. 7.b.** Recorded signal on the computer

## 3. Experiments and Results

Based on the proposed system, the authors conduct designing the printed circuit board (PCB), selecting components, assembling, and weldering all the components onto the PCB. The completed circuit is illustrated as Fig. 7. To evaluate performance of the system, the author separated experiments into two aspects: measurement of static and dynamic impedance.

For evaluating the static impedance measurement of the designed system, the simplified human body impedance model circuit with RC in series [21] was used. The resistor was chosen to be 500 Ω and the capacitance was 10nF, the peak-peak amplitude of the current was 500 µA. Then the frequency of the current source was increased from 5 kHz to 400 kHz. The measured and theoretical calculation of base impedance are represented on the same graph (Fig. 8) for comparison. The coefficient of determination, denoted R2 is used to measure the degree of correlation between the measured impedance and theoretical calculating impedance. The R2 is 0.9815.

For evaluating the dynamic impedance measurement of the designed system, the authors use a bio-impedance simulator from Niccomo (from Medis) with well-known waveforms and values of bio-impedance signal to generate the standard signal source. The two samples of signal have the same length and sampling rate (200 sps) that is convenient for calculating the error of the proposed system. Because amplitude range of two digitalized samples of signal are not identical due to using different analog-to-digital converters, our measured sample of signal will be scaled to fit the standard sample based on the maximum and minimum value of sample before calculating the error. The simulator has two type of waveforms with the two different heart rate (68 and 72 beat/min). The experiment was implemented for 30s duration for each waveform. The two criteria to evaluate the errors of the measured samples compared to the standard samples are root mean square error (RMSE) and relative (normalized) root mean square error (rRMSE).

$$RMSE = \sqrt{\frac{1}{n}\sum_{t=1}^{n}(\hat{y}_t - y_t)^2} \tag{4}$$

$$rRMSE = \sqrt{\frac{1}{n}\sum_{t=1}^{n}\left(\frac{\hat{y}_t - y_t}{\hat{y}_t}\right)^2} \tag{5}$$

After calculating, the RMSE and rRMSE for waveform 1 are 17.14 and 0.0857%; RMSE and rRMSE for waveform 2 are 13.58 and 0.0679% correspondingly. The graphs of signal acquired from the proposed system based on the standard simulator and the one acquired from equipment accompanying with the simulator (waveform of type 1) are shown in Fig. 9 and Fig. 10.

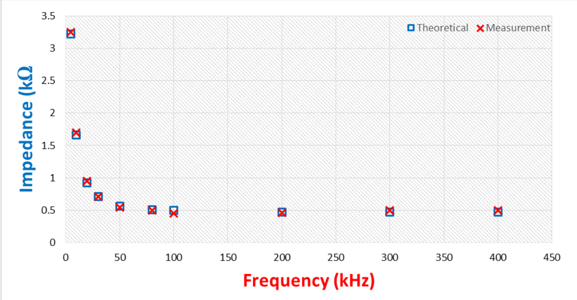


**Fig. 8.** Theoretical and measured impedance when the frequency was changed.

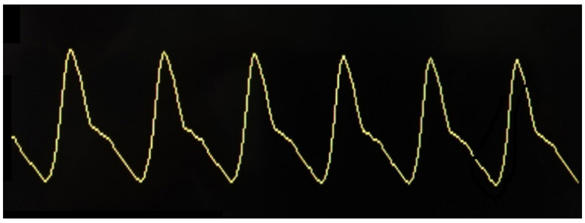

**Fig. 9.** Signal acquired from the Niccomo equipment accompanying with the simulator

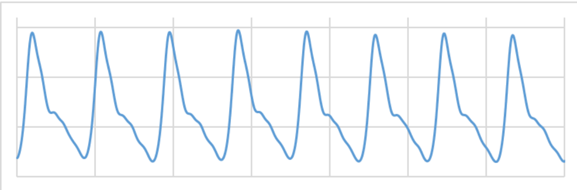

**Fig. 10.** Signal acquired from the proposed system based on the standard simulator

## 4. Conclusion

This paper introduces a low-cost system able to record the rheoencephalography signal as the base for researching about characteristics of REG waveform supporting diagnosis and assessment of cerebral circulation. The REG signal obtained from the proposed system has been already proven to have high fidelity that creates premises for further processing. In further studies, the authors expect to reseach and develop processing algorithims in order to extract more helpful information from the acquired signal based on the inheritance of these researching results.

## Acknowledgment

This research is funded by the Hanoi University of Science and Technology (HUST) under project number T2017-PC-164.

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