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Correlation of PPG and Accelerometer Signals

Dhanya V
Department of Electronics and Communication Engineering,
Amrita School of Engineering, Amrita Vishwa Vidyapeetham
Coimbatore-641112, India

Kayalvizhi N
Department of Electronics and Communication Engineering,
Amrita School of Engineering, Amrita Vishwa Vidyapeetham
Coimbatore-641112, India

Abstract **: Accelerometers are being used in biomedical applications for assessing the functioning of the heart by measuring the vibrations created due to pulses. They are being used in smartphones and smartwatches to find heart rates. A pulse sensor is an optical sensor which takes optical input and requires a photodiode to absorb the output radiations, whereas accelerometers require only vibrations as input. So pulse sensors can be replaced by compact and more sensitive accelerometers. The signals were acquired using the SEN-11574 pulse sensor and ADXL335 accelerometer from 10 volunteers. The main peaks and secondary peaks of the accelerometer signals and the main peaks and secondary peaks of the PPG signals were found. The time difference between the peaks was calculated for both the signals. This peak to peak time intervals are indicators of heart rate. The coefficient of correlation between PPG and accelerometer signals was found for each sample, and the average coefficient of correlation for the acquired ten samples was found to be 0.9912, which implies a strong positive correlation between the signals.**

Keywords—Accelerometer; PPG acquisition; Correlation between PPG and Accelerometer signals

I. INTRODUCTION

An accelerometer is an electromechanical device used to measure static or continuous accelerations. The Micro-electro Mechanical System (MEMS) accelerometers are highly sensitive, consume less power and they have three axes that are used for measuring vibrations. The signal acquired using an accelerometer is a mechanical signal. The accelerometer is placed on the carotid artery to acquire the mechanical cardiac signal as it is the measure of the displacement of blood pulse in the arterial wall [1] [2]. This technology is used in smartwatches to calculate heart rate [3] [4] [5]. A Photoplethysmogram (PPG) is a non-invasive optical method to obtain the volumetric changes of blood in the microvascular bed of tissue. The change in volume is due to the absorption or reflection of light by the blood vessels in living tissues [6] [7]. PPG signal can be obtained either by a reflective or absorptive method. PPG signal contains the main peak and a secondary peak. The peak after the dicrotic notch is the secondary peak which corresponds to the transient increase in aortic pressure upon the closure of the aortic valve by the reflected waves. This notch is usually used as a marker for the end of the ventricular ejection period. Blood pumped from the heart will lead to the main peak. The secondary peak is due to the reflection of blood in the vessel [8]. It is a strong indicator of cardiovascular events. PPG signal is used to determine pulse-rate, arterial blood oxygen saturation (SpO2), and respiratory rate. Due to the development in technology, Pulse Transit Time (PTT), Pulse Wave Velocity (PWV), and Blood Pressure (BP) can be determined using PPG signal [1]. A PPG signal is also a bio-mechanical signal as it synchronizes with a person's heartbeat. And so an accelerometer signal can be correlated with a PPG signal. Both the PPG and accelerometer signals are acquired from the carotid artery.

II. MATERIAL AND METHOD

A. Photoplethysmogram

Photoplethysmogram (PPG) is a simple, low-cost optical technique for detecting volumetric changes in blood volume in tissue micro-vascular bed. The blood volume in the capillary increases through the systole and decreases through the diastole. A PPG circuit consists of one or two Light Emitting Diode (LED) of different wavelengths and a photodiode. The light with a larger wavelength will penetrate deep into the tissues [9]. There are two modes of PPG signal acquisition. In transmission type, the LEDs and the photodiode will be on the opposite sides while they will be on the same side in the case of reflectance type [10] [11]. The reflectance type PPG sensor (SEN-11574 Pulse Sensor) is used where the light reflected by the blood vessels will be detected by the photodiode. PPG signal consists of an AC (pulsatile) component and also a DC (non-pulsatile) component [12]. The AC component is due to the reflection of light by pulsating components like arteries, arterioles, and capillaries. The DC component is due to the reflection of light by static skin surface, epidermis, dermis, and sub-cutis. The AC signal corresponds to the synchronized cardiac changes in blood volume and the DC component consists of small frequencies due to sympathetic nervous activity and respiration. The principle of acquiring the PPG signal is based on Beer-Lambert's Law which states, the quantity of light absorbed by a substance dissolved in a transmitting solvent is proportional to the concentration and path length of light through the solution. The reflected light intensity decreases exponentially from the initial intensity of light passed with the distance passed through the absorbing medium [9] [13] [14].

B. Accelerometer

ADXL335 piezoelectric MEMS accelerometer is a highly sensitive three (X, Y, and Z) axis accelerometer with an analog sensor. In piezoelectric accelerometers, the capacitance will change corresponding to any tilt or small vibration. This change in capacitance is processed to voltage and the voltage obtained is the measure of respective accelerations. This accelerometer when placed on the carotid artery measures the accelerations which are due to the arterial wall displacements on the skin which indicates the propagation of blood pulse through the arteries [1].

The pulse sensor and the accelerometer are placed on the carotid artery to acquire the PPG and accelerometer signals. These sensors are powered by a 3.3 V power supply. The PPG and accelerometer signals must be amplified and conditioned to ensure that the signals are noise-free. The signal conditioning for the acquired signals is done as per the block diagram shown in Fig. 1 and it is powered by a 10V power supply. A sixth-order Bessel high pass and a sixth-order Bessel low pass filter with a cut-off frequency is designed to obtain 0.5 Hz and 20 Hz respectively. A Bessel filter produces a linear phase to frequency relation. It also provides a constant delay with a linear phase shift along with a good step response. A high pass filter also known as the low-cut filter will pass all the signals which are above the given cut-off frequency. To prevent the saturation of our operational amplifier, dc elimination is done using a high pass filter. The signal obtained from the high pass filter is relatively small in magnitude which must be amplified for further analysis. A non-inverting amplifier is used with a gain of 10.375 V. The high input impedance and low output impedance provided by this gain amplifier makes this circuit stable. A low pass filter also known as the high-cut filter will pass the signals with a frequency below the given cut-off frequency. It is used to reduce the high-frequency noises and fluctuations. The frequency response of the signal conditioning unit is shown in Fig. 2.

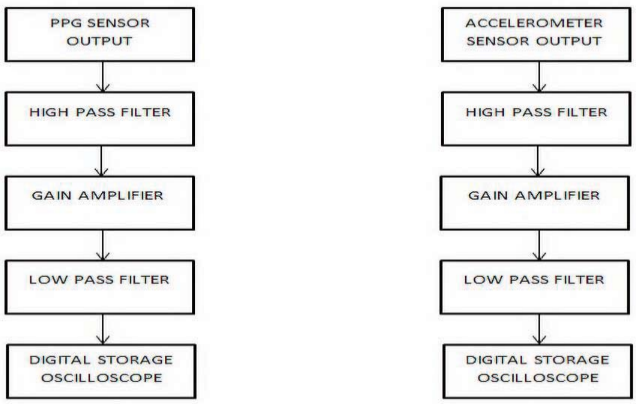

Fig. 1. Block diagram of signal acquisition

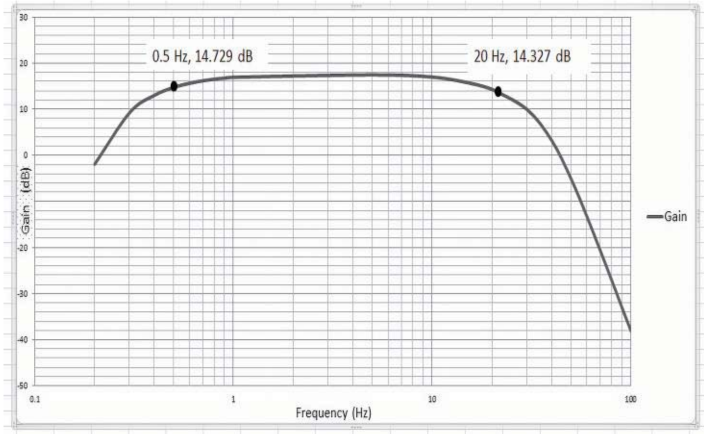

Fig. 2. Frequency response of signal conditioning unit

The signal output obtained from the low pass filter is given to the Digital Storage Oscilloscope (DSO) to view the quality of the acquired signal. The repeatability and reproducibility of our method were checked. The final experimental setup of our work is shown in Fig. 3. Simultaneous acquisition of PPG and accelerometer signal for sample 1 is shown in Fig. 4. The signal in yellow color indicates the “Accelerometer signal”, and the signal in green color indicates the “PPG signal” of sample 1. To perform further analysis, the acquired signals are processed using MATLAB software.

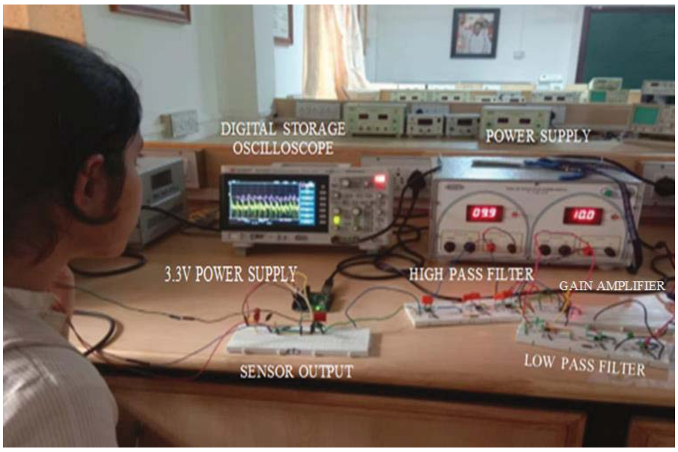

Fig. 3. Acquisition of PPG and accelerometer signal

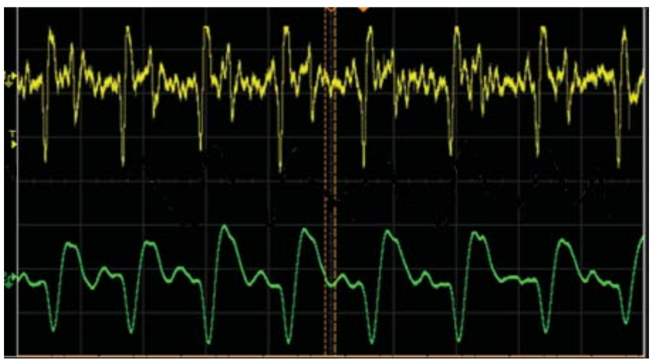

Fig. 4. PPG and accelerometer signal

The main peaks and the secondary peaks were located for both the PPG and accelerometer signals using MATLAB. The peak to peak time intervals is the indicators of heart rate [15]. In Fig. 5 and Fig. 6 the peaks are located for sample 1 and highlighted with red spots. Fig. 5 represents the 't1' as time period between the two main peaks of the accelerometer signal and 't3' is the time interval between the two secondary peaks of the accelerometer signal. Fig. 6 't2' is the interval of time between the two main peaks of the PPG signal and 't4' represents the time period between the two PPG secondary peaks.

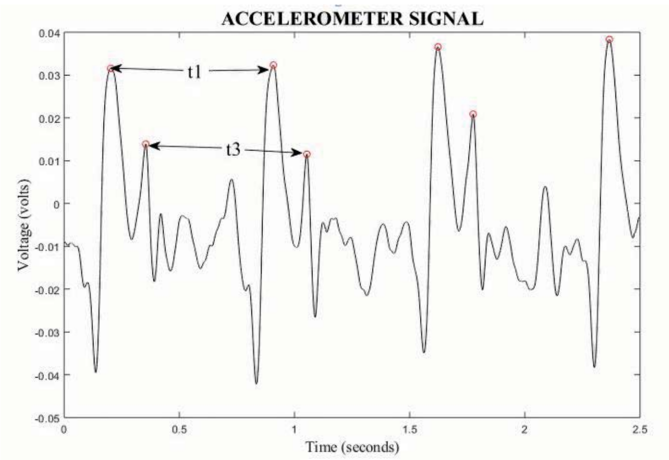

Fig. 5. Accelerometer signal

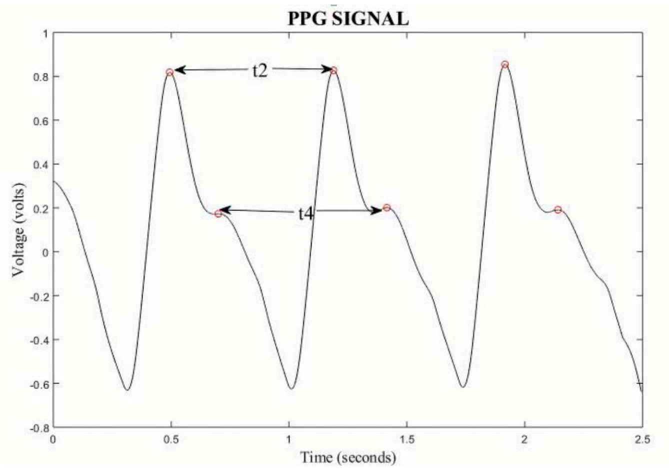

Fig. 6. PPG signal

Table I describes the comparison of time period between the main peaks of the PPG signal with the time period between the main peaks of the accelerometer signal for sample 1. In the same manner, Table II illustrates the comparison of time intervals between the secondary peaks of the PPG signal with the time period between the secondary peaks of the accelerometer signal for sample 1. In Table III, the time period between PPG main peak and PPG secondary peak was compared to the time interval between the accelerometer main peak and the accelerometer secondary peak for sample 1.

TABLE I. TIME PERIOD DIFFERENCE BETWEEN THE MAIN PEAKS IN ACCELEROMETER AND PPG SIGNALS

Accelerometer Main Peak Instants s	Diff between two Main peaks (t1) s	PPG Main Peak Instants s	Diff between two Main peaks (t2) s	Diff (t1~t2) s
4.3957	0.6809	4.6882	0.6803	0.0006
3.7148	0.6501	4.0079	0.6691	0.0190
3.0647	0.6985	3.3388	0.6923	0.0062
2.3662	0.7438	2.6565	0.7314	0.0124
1.6224	0.7136	1.9151	0.7272	0.0136
0.9088	0.7059	1.1879	0.6949	0.0110
0.2029		0.4930		

TABLE II. TIME PERIOD DIFFERENCE BETWEEN THE SECONDARY PEAKS IN ACCELEROMETER AND PPG SIGNALS

Accelerometer Second Peak Instants s	Diff between two Second peaks (t3) s	PPG Second Peak Instants s	Diff between two Second peaks (t4) s	Diff (t3~t4) s
4.5535	0.6846	4.9498	0.7076	0.0230
3.8689	0.6739	4.2422	0.6566	0.0173
3.1950	0.6868	3.5856	0.7059	0.0191
2.5082	0.7319	2.8797	0.7369	0.0050
1.7763	0.7220	2.1428	0.7262	0.0042
1.0543	0.7000	1.4166	0.7128	0.0128
0.3543		0.7038		

To examine the correlation between the PPG and accelerometer signals correlate both the signals for all the ten samples. In Table IV, the coefficient of correlation between PPG and accelerometer signals was calculated for all the ten samples. The coefficient of correlation $'r'$ was found using [8]:

$$r = \frac{\sum xy - \sum x \sum y/n}{\sqrt{\left[\sum x^2 - \frac{(\sum x)^2}{n}\right]\left[\sum y^2 - \frac{(\sum y)^2}{n}\right]}}$$

Where $'x'$ and $'y'$ are the data points of PPG and accelerometer signals and $'n'$ is the length of the signal. In certain cases, the secondary peak or the dicrotic notch may not be seen. Three methods can be opted to overcome this problem such as the Symmetrical curve fitting method, Gaussian curve fitting method, and Adaptive curve fitting method.

TABLE III. TIME PERIOD DIFFERENCE BETWEEN THE MAIN PEAK AND SECONDARY PEAK OF ACCELEROMETER AND PPG SIGNALS

Accelerometer Main Peaks Instants S	**Accelerometer Secondary Peaks Instants** s	**Difference (main ~ sec) Accelerometer (a)** s	**PPG Main peaks Instants** s	**PPG Secondary Peaks Instants** s	**Difference (main ~ sec) PPG (b)** s	**Difference (a ~ b)** s
4.3957	4.5535	0.1578	4.6882	4.9498	0.2616	0.1038
3.7148	3.8689	0.1541	4.0079	4.2422	0.2343	0.0802
3.0647	3.1950	0.1303	3.3388	3.5856	0.2468	0.1165
2.3662	2.5082	0.1420	2.6565	2.8797	0.2332	0.0912
1.6224	1.7763	0.1539	1.9151	2.1428	0.2277	0.0738
0.9088	1.0543	0.1455	1.1879	1.4166	0.2287	0.0832
0.2029	0.3543	0.1514	0.4930	0.7038	0.2108	0.0594

TABLE IV. COEFFICIENT OF CORRELATION

Sample Number	**Age**	**Coefficient Of Correlation**
1	21	0.9995
2	21	0.9993
3	21	0.9718
4	20	0.9926
5	21	0.9897
6	21	0.9964
7	21	0.9931
8	20	0.9912
9	19	0.9805
10	20	0.9981
Average		0.9912

III. RESULTS AND DISCUSSION

From Table I, it is found that the time interval difference between the main peaks of the PPG signal and accelerometer signal is very less, and it is in the range of 0.001 to 0.02 seconds. The time period difference between the secondary peaks of PPG and accelerometer signals was calculated in Table II. The secondary peak time difference was also found to be very less in the range of 0.004 to 0.02 seconds. The difference in the time period between the main peak and secondary peak of the PPG signal and the time period between the main peak and secondary peak of the accelerometer signal was calculated in Table III. The deviation was found to be in the range of 0.06 to 0.1 seconds. This peak position mismatch is due to the high-frequency noises in the vibration sensor. The coefficient of correlation for PPG and accelerometer signals for each sample was calculated in Table IV. The average coefficient of correlation was found to be 0.9912, which shows a strong correlation between the PPG and accelerometer signals.

IV. CONCLUSION AND FUTURE SCOPE

The sample signals were collected from healthy volunteers (females) aged between 18 and 22 years. Written consent was obtained from our volunteers after explaining the purpose and procedure of our work, and the volunteers are requested to relax for 10 minutes to avoid motion artifacts in the signal. After a sufficient time of relaxation, the signals were acquired from the volunteers. The quality of the acquired signals was verified using the DSO and the process was repeated to obtain accurate signals from the carotid artery. For works that do not deal with the time period, calculating the number of peaks is sufficient because this peak position mismatch will not create any problem. The time interval between the main peaks corresponds to the heart rate. The average correlation coefficient, 0.9912 shows a strong correlation between the PPG and accelerometer signal. The main peak of accelerometer signal corresponds to the PPG main peak and the accelerometer secondary peak corresponds to the PPG secondary peak.

In the future, this work can also be done to acquire the signals from the radial artery. Acquiring signals from the radial artery will be even more comfortable. The coefficient of correlation or precision can be improved by increasing the accelerometer sensor sensitivity. Further, it can be extended to find the Pulse Transit Time, Pulse Wave Velocity and also in measuring Blood Pressure.

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