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A NOVEL PHOTOPLETHYSMOGRAPH SENSOR PROBE DESIGN FOR MOTION ARTIFACT DETECTION: A COMPARISON STUDY WITH THREE AXIS ACCELEROMETER

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ABSTRACT

Photoplethysmography (PPG) sensors have become widespread in most of the healthcare categories; its drawback is unreliable during non-stationary states. Adaptive noise cancellation is one of the several techniques have existed to address this issue. The problem of implementing this method still lacks for total detection of induced noise due to the motion. In this work, a new method was introduced for noise detection based on novel PPG sensor probe design by adding a covered photodetector (CPD) as a motion artifact reflector, in addition to the main photodetector (MPD). Experiments of several motion kinds were executed to the tied (CPD) with the accelerometer. Data analysis for the collected signals showed a lengthy convergence between the amplitude fluctuations in the time domain. The CPD precisely indicated all the fundamental frequencies of various induced noise, unlike the accelerometer. Using these photodetectors, the CPD as noise reflector and the MPD to track the contaminated PPG signal is more reliability than other approaches. Implementing this method ensures a high-level accuracy and reducing the cost of repeated false examinations. Furthermore, simple software computation and low power consumption. Practical application of this study will be presented in our next work.

Keywords: *Photoplethysmograph, Motion Artifacts, Accelerometer, CPD, MPD*

1. INTRODUCTION

Photoplethysmography is a noninvasive method to measure changes in arterial blood flow through the skin utilizing infrared light and photodetector. PPG technique has been accepted by the International Standards Organization (ISO) and the European Committee for Standardization as the standard non-invasive measure of oxygen saturation level since 1987[1]. PPG technique has been implemented in many different medical settings, including clinical, physiological monitoring (blood oxygen saturation level, Heart Rate, Blood Pressure, Cardiac Output, Respiratory Rate), Fetal Heart Rate and person's identity [2-5]. Despite the many PPG signal advantages as an easy to set up, comfortable, inexpensive compared to the other types of such medical devices [6]. However, PPG signals could be easily affected by intended or unintended motion in the measurement process which may conducive to the incorrect interpretation of the reported PPG signal waveform which can be used for diseases classification [7, 8]. So it is not straightforward to remove the motion artifacts from the PPG signal.

Valuable efforts were spent to cope with resulted mistakes in measurements during motion state by using different techniques as reported by [9-13]. In a comparative study [14] of several currents used methods for the PPG signal processing while the non-stationary state was concluded that each of those methods has its advantages and disadvantages. Also, the mentioned study indicated that the ANC technique is not the worst of the others and could be better if a proper hardware

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provided the reference noise signal instead of using the synthetic way, as the both are traditionally utilized for this task.

What concerns us is the ANC method; the main drawback of its implementation is providing the actual reference noise signal as a major factor in the quality of the adaptive filter performance. Usually, it is provided by two approaches an additive hardware or synthetic noise.

Also, the Independent Component Analysis (ICA) technique [10] was used to address the same issue depending on statistical independence assumption between motion artifact and heart pulsation. The difficulty of the ICA application lies in the necessity of providing multiple pre-processed signals to overcome the interrelationship between heartbeat rhythm and the motion artifact [15]. However the preferred application is for ANC being based on fewer complexity calculations, the both techniques may do the same effective performance in case of producing entirely separate motion artifact.

An added another transducer such 3-axis accelerometer attached in the same area of the subject test to reflect the effect of motion. Many researchers concluded that there is no significant relationship between motion artifact and accelerated data from the added accelerometer in PPG sensor and what associated with extra PPG sensor, additional sources of noise can be caused [16-19].

Another Approach is by synthetic noise through the use of PPG signals itself that recorded from wearable oximetry devices to mathematically estimate the reference noise as being employed in studies [20, 21]. The synthetic noise approach in mentioned studies is not efficient to meet robust and sudden motions during performing some physical exercises, furthermore it is computationally intensive, which may not be suitable for systems with limited resources [22, 23].

Hence, the need for reliable approach ensures the entire detection for the induced noise due to any motion, is still in need for safe implementing of the PPG sensor leads to a precise monitoring of various heart diseases during daily motion life.

In this paper, we demonstrate a new approach to providing the noise reference signal highly correlated to the induced motion effects PPG signal due to the motion artifact, based on modified traditional PPG sensor. The idea was built on prior knowledge of adaptive filter [24] and Photodiode Characteristics [25]. The modification for classic PPG sensor is introduced by adding a covered photodetector CPD away from light effect as a noise reflector (noise reference signal in ANC, in addition to the main photo detector (MPD) which is customized to provide the corrupted PPG signal (primary signal in ANC). This approach ensures completely same source for both signals and avoids the electronic noise effect, which usually is neglected on traditional methods for such sensitive signal processing. Validation of the fact that the CPD as a reflector for motion artifact would be in a manner of fastening together the accelerometer and the CPD, and exposed to different movements; along with X, Y and Z axis, also during silence state. Calculating the resulted two signals of CPD and the combined signal of 3-axis accelerometer signals for all mentioned activities, and then analyzing amplitude fluctuate in the time domain and Fast Fourier Transform FFT peak plots in the frequency.

2. METHODOLOGY

2.1 Motivation

The conflict between researchers to address the fundamental obstacle of unreliable measurements during motion state for the PPG sensor motivated us to investigate the real reasons stand behind this drawback in more realistic perspective. Some of the researchers adopted the added hardware like the accelerometer and others went to utilize different algorithms to compensate the motion effect in processing the corrupted PPG signal without achieving the optimum accurate. Therefore we involved a new concept of similar twin-photodetectors as two eyes, one to generate the distorted PPG signal while the other one would be covered up from the light effect to reflect the same distortion accompanied by the distorted signal simultaneously. As an efficient solution to provide a proper environment for ANC and ICA Applications, and to avoid the electronic noise emergence in the case of adding extra hardware, also the occurred frequency overlap that prevents the exact algorithmic estimations.

2.2 Background of Study

Since the photodiode is the critical component in generating the PPG signal, also it exposes to various types of noise, the manufactured PPG sensor is an electronic instrument subjects to Equipartition theorem [26]. This theorem states that: (Each degree of freedom of any system fluctuates with energy equal to 1/2 kBT=2*10-21 J) at the standard temperature of 290 K. (where kB =1.38 x 10-23 J/K, is the Boltzmann constant and T

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the absolute temperature). Motions give rise to a random electric current even in the absence of an external electrical power source. Electronic noise in electronic systems constraints the whole performance of the systems. Therefore, there is a paramount correlation between the motion artifact and the induced electronic noise in photodetectors.

From the photodiode voltage-current characteristic, when a reverse bias is connected a reversed saturation current I sat does exist, it relates to the generated dark current Id as being calculated in equation (1) and highlighted in figure 1 [27-29].

$$I_d = I_{sat}\left(e^{\frac{qV_A}{K_B T}} - 1\right) \quad (1)$$

Where Id is the photodiode dark current, Isat is the reverse saturation current relates to the dark current; q is the electron charge. VA is the applied bias voltage, KB = 1.38 x 10-23 J/K, is the Boltzmann constant, and T is the absolute temperature (273 k = 0 °C).

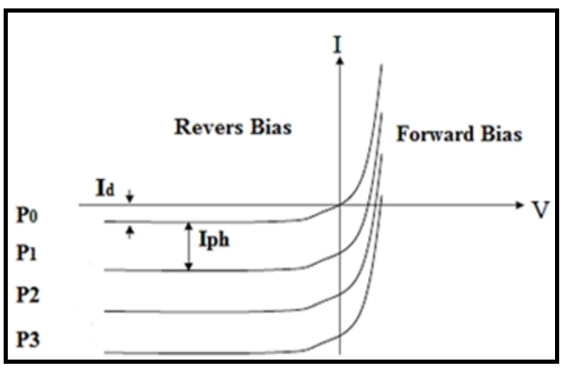

Figure 1. Characteristic I-V Curves Of An Optoelectronics Photodiode For Reverse And Forward Bias Modes Of Operation. P0-P3 Represents Different Light Levels, Starting From Dark State And Up.

$$I_{Total} = I_{sat}\left(e^{\frac{qV_A}{K_B T}} - 1\right) - I_{Ph} \quad (2)$$

Hence during reverse bias and no incident light, a small dark current occurs and with increasing the incident light, the generated photocurrent IPh will also increase depending on incident light power P as in equation (2). Also from the photodiode noise characteristic, the photodiode noise acts the induced noise because of motions effect that raises the random motion of electron holes to flow due to incident light and dark current effect. The photocurrent noise can be specified in two main sources; Shot Noise (ISN) which exists as a result of the statistical fluctuations during the generated photocurrent in both forward and reverse bias in addition to the Johnson noise (IJN) which is related to shunt resistance available in electronic photodetector circuit. The total induced noise (ITN) in photodetectors can be calculated by the (equation 3) [25].

$$I_{TN} = \sqrt{I_{SN}^2 + I_{JN}^2} \quad (3)$$

2.3 Novel PPG Sensor Probe Design

Exploiting the similar property of photodetector in the presence of light or dark state [25] led to reconsider the classical PPG sensor probe design. Figure 2 shows the block diagram of the new PPG sensor probe design with two reverse biased photodetectors in the same position setting would be a meaningful solution for PPG signal processing in ANC technique.

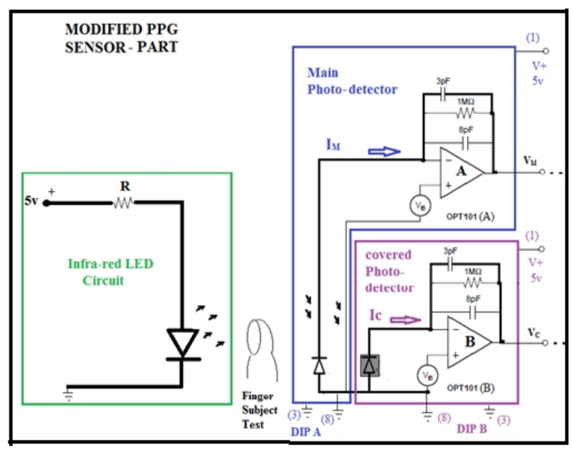

Figure 2. Block diagram of the new PPG sensor probe design.

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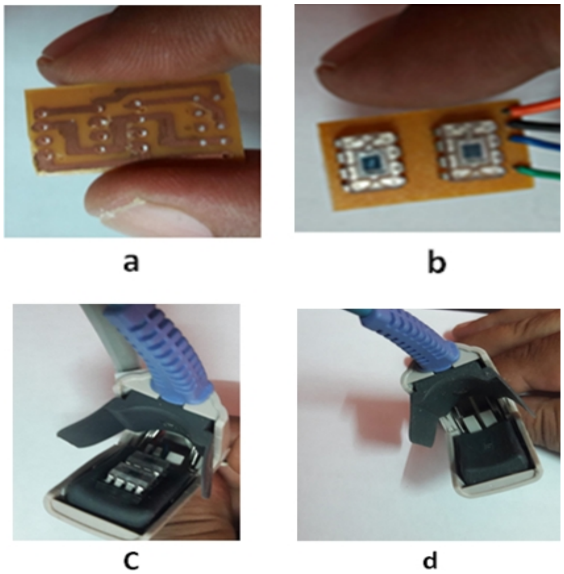

Figure 3. (a) is the required PCB for PPG sensor probe, (b) is the PCB design for suggested sensor probe, (c) and (d), are the new and classical PPG sensor layout respectively.

One of the photodetectors will be covered up from light effect, and light will illuminate only the second one. The occurred photocurrents in both photodetectors meet the same induced noise, but the different is the bright one will contain the PPG data as well. In such a way we would provide corrupted PPG data by the illuminated photodetector and the induced noise by the covered one. Utilizing adaptive noise cancellation with the minimum required computation algorithm free-noise is sufficient, and the PPG signal would be obtained away from the complexity of estimation process as well.

The idea of presenting this design is to produce an alternative method for routine use of 3-axis accelerometer as a reference sensor to provide the noise reference signal in applying the ANC technique. In the design part, a traditional PPG sensor was modified to be with one infra-red LED and two amplified photodetectors (APDs) type (OPT101) having been connected in parallel as in Figure 1. The generated photocurrent IM which is proportional to the light power and wavelength of incident infrared light would be converted to a voltage by the configured trans-impedance of 1MΩ. The resulted voltage forms the output VM of the main amplified photodetector A (MAPD - A) which gives the corrupted PPG signal and the motion artifact effect in addition to the electronic noise.

The another output VC of the covered amplified photodetector B (CAPD - B) which results by passing the generated dark current IC through the trans-impedance of 1MΩ, would give the induced motion artifact noise that has been assumed, they are the same portion in both amplified photodetectors. Both photodetectors are in reversed biased (photoconductive mode). VC is completely unlike the VM on a paramount issue that they are not correlated in term of PPG while in the duration of the motion artifact noise tends to be extremely correspondent. The aim of this design is to obtain the reference signals for adaptive noise cancellation processing later. Typically, the adaptive filter is fed with two types of signal. Primary signal is the desired signal contaminated by noise while the second represents the reference signal of noise that corrupted the wanted signal. The primary signal can be characterized as in equation (4) due to resulted output from the main amplified photodetector (MAPD).

V_M from MAPD (A) = Clean PPG signal + Motion Artefact + Electronic Noise (4)

Whereas the noise reference signal can be characterized due to the output voltage from the covered amplified photodetector (CAPD) as in equation (5).

VC from CAPD (B) = Motion Artefact + Electronic Noise (5)

With these characterized signals adaptive filter can do the task of filtering contaminated signal and update its coefficient upon the provided noise reference signal.

3. VALIDATION STUDY

To justify the use of the cpd to determine the real effect of motion artifact during implementing the ANC for PPG signal processing, instead of 3-axis accelerometer which is customized to indicate only the motion according to gravity influence. Two types of analyzing have been done. Series of experiments were conducted using both sensors and were exposed to different kinds of movement along with x, y, and z axis. The resulted data from two sources, the CPD, and the acceleration were recorded for further analyzing as explained in (3.3).

3.1 Data Acquisition Set-up and Protocol

Data of 3-axes accelerometer (AD335, Analog Devices) were collected separately for each X, Y, and Z axis in addition to the data from a covered photodetector, utilizing the four channels DAQ-NI 9215 as shown in Figure 4b.

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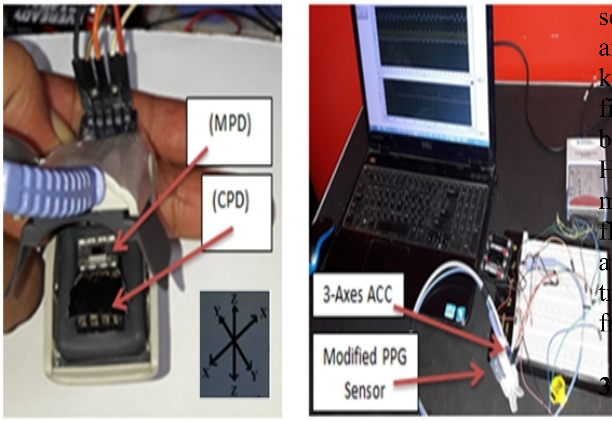

a b

Figure 4. (a) is the state of the main photo detector (MPD) and covered photodetector during motion execution, (b) is the setup of data acquisition.

All data were sampled at 100 Hz and 300 samples per channel using LabVIEW 2015 (National Instruments Corporation). The three channels of X, Y, and Z axis have been combined into r due to the equation (6) into one signal.

$$r = \sqrt{X^2 + Y^2 + Z^2} \tag{6}$$

where r, is the combined signal of the 3-axis accelerometer separated channel signals x, y and z. All the utilized hardware and software parameters of resulted in this approach layout, as revealed in sections of design and validation, are summarized in Table 1, as following.

Table 1. Key intrinsic for implemented hardware and software parameters.

I. Key Design Parameters	II. Types	III. Values
IV. Traditional PPG sensor	V. Nellcor DS100A	**VI.** –
VII. Amplified photodetector	VIII. OPT101	IX. –
X. 3-axes Accelerometer	XI. AD335	XII. –
XIII. Four channels DAQ.	XIV. NI 9215	XV. –
XVI. Sampling rate	XVII. –	XVIII. 100 Hz
XIX. Samples per Channel	XX. –	XXI. 300 samples
XXII. Butterworth low-pass filter	XXIII.	XXIV. 15 Hz

Data were collected in two states during motion and silence state. Three motion types by moving the hand holding the both devices along with X, Y, and Z axes were executed as in figure 4a. For the second state, devices were left on the table without any effect of a fan or air-condition in an attempt to keep them under the same external impacts as in figure 4b. After that, the acquired data was filtered by a second order Butterworth low pass filter of 15 Hz. Then, the signals were plotted to observe the match of the recorded signals during the amplitude fluctuate in the term of time domain for the motion and no motion states. Finally, both cases were transformed into frequency domain using FFT for frequency domain analysis.

3.2 Amplitude Fluctuations

The fluctuations of all signals amplitude that involve the motion of X, Y, Z, r and CPD signal were monitored during three types of relatively fast motion of frequent around 6 Hz in term of time. The kind of trends of these fluctuations can indicate the primary relationship among them.

3.3 Fast Fourier Transform

The Fast Fourier Transform (FFT) is a mathematical way to convert a function of a time domain into frequency domain. Fourier analysis (FA) of a periodic function indicates the extraction of series sine and cosine waves to reconstruct the function [30, 31]. The equation (7) defines the Fourier Transform:

$$X(f) = F\{x(t)\} = \int_{-\infty}^{\infty} x(t)\, e^{-j2\pi f t}\, dt \tag{7}$$

where x(t) is the time function, x(f) is the fast Fourier transform function and (ft.) is the analyzing frequency. Calculating the FFT peaks of the three channels of 3-axis ACC and their combined signal in addition to the covered photodetector signal, then comparing the resulted peaks must be matched to each other in same frequency domain.

4. RESULT AND DISCUSSIONS

4.1 Time Domain Analysis

During motion state, 3-axis acceleration. X, Y, Z, resultant acceleration r and the CPD, their amplitude trends for continuous 3 seconds data were observed. Figure 5 of 3 windows showed the amplitude fluctuations during the motion along the X axis as an example, where the data was filtered, and the DC component removed. Despite, the small difference of other intensive fluctuations in CPD signal, belongs to the variance noise property of each device within time [27]. Although, the amplitude fluctuations indicate a noticed convergence between the two approaches as reflectors for the motion effect. From the bottom

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part of the mentioned figue, it is clearly noticed that the magnitude of accelerometer amplitude was higher than CPD amplitude as it is designed for measuring motion and follows the Gravity impact during movement within the three axes.

For the silence state, the both devices outputs fluctuate as a result of the environment effect such electromagnetic devices which also results in an electronic noise [28, 29] differs from device to another as shown in figure 6. In this state, what drawn our attention is that the amplitude magnitude of CPD is unlike in the previous state of motion because the dark current Id effect always exists. For such instant, the generated dark current

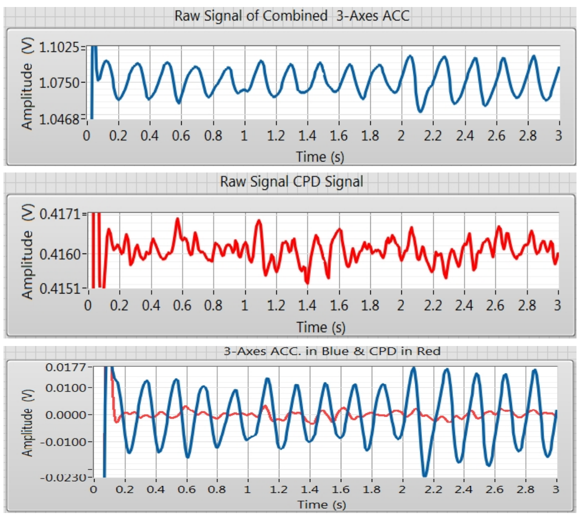

Figure 5. Top And Middle Windows For Raw Data Of Acceleration And CPD Signals, The Bottom, Is The Filtered Signals With Removed D.C Component.

Id would represent the whole induced noise which is the same portion simultaneously will be induced in MPD of the proposed design.

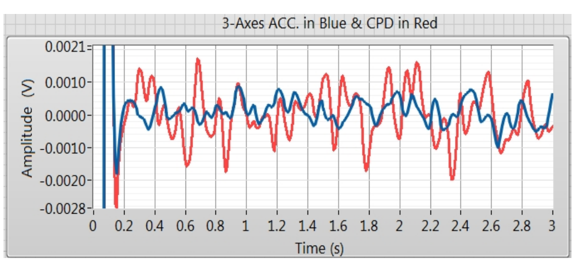

Figure 6. Amplitude fluctuation of both acceleration and CPD signals in silence state for continuous 3 seconds.

4.2 Frequency Domain Analysis

In addition to what we had discussed about the amplitude fluctuate in the two different states, correspondence of plotted FFT peaks for the CPD and 3-axis acceleration in the silence, state shows how the both devices approximately share the same harmonic spectrum amplitudes. Although in a motion state they also share the same plotted spectrum in the frequency domain, they are different in term of the energy signals distribution. Figure 7 Highlights the close convergent of total fundamental harmonics as it is pointed by arrows for maximum and minimum in 20 Hz during silence state for continuous 3 seconds.

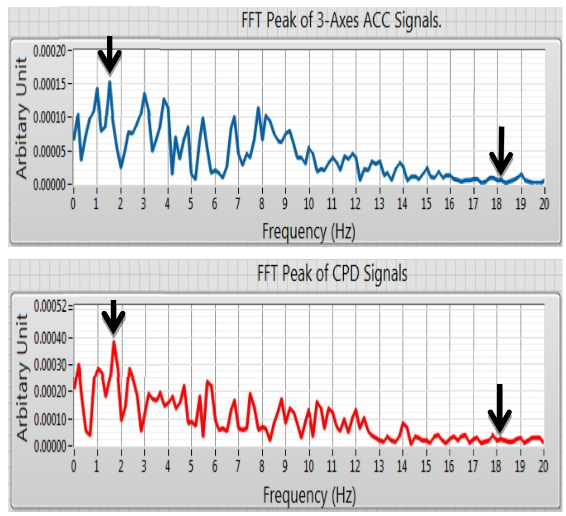

Figure 7. FFT Plot During Silence State For Both Covered Photodiode And Accelerometer.

In the (Figures 8, 9 and 10) the FFT peaks were plotted for acceleration and CPD signals in the same frequency band and time for the previous state for motions along with X, Y, and Z respectively. For the first motion plot along with X axis figure 8 (top) indicates that acceleration device has the precedence task of determining the spectrum of the movement as a customized sensor for this limited function. Whereas in the bottom part of the same figure, CPD FFT peak plot has pointed all the affected frequencies according to the effect priority of various impacts and not only the motion effect, unlike for the acceleration plots.

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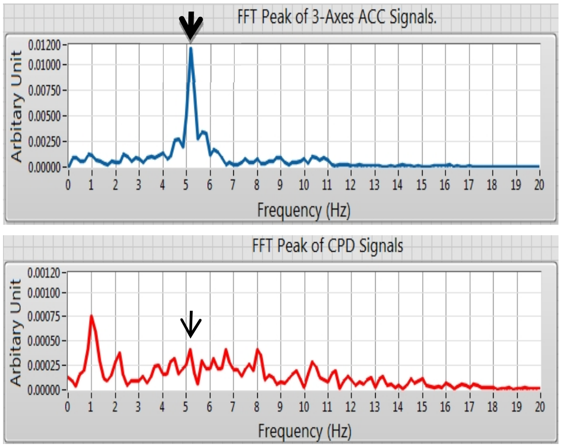

Figure 8. FFT plot during motion along with X-axis for both covered photodiode and accelerometer.

The same concept can be deduced by examining the (Figures 9 and 10). Which belong to motions along with Y and Z axes, even more than the specifical accuracy for each harmonic that can exceed the expected frequencies overlap as revealed in figure 9 bottom. So undoubtedly could be guided by the existed results that the best solution to determine the correspondence noise in ANC applications is the recruitment of the same type source of active ingredient in measurements required high accuracy.

In previous study [32] two photodetectors were used to indicate two measurements at the same time furthermore the novel work in [33] utilized two LEDs of different wavelength lights (Red and Green) and one photodetector to get two signal values according to switching time control. But both studies have adopted the comparative differential processing between the collected signals to remove the occurred noise. The reported results were limited to the motion speed due to the need of constant equal amplitudes for generated signals as precondition for an efficient application of the differential processing approach to remove the noise and this is not easy be achieved during motion.

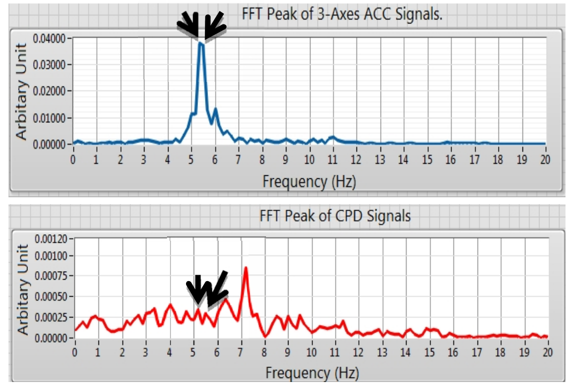

Figure 9. FFT plot during motion along with Y-axis for both covered photodiode and accelerometer.

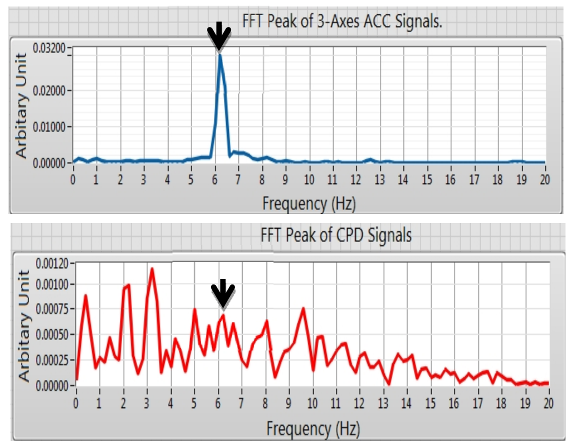

Figure 10. FFT plot during motion along with Z-axis for both covered photodiode and accelerometer.

Application of this approach results in an essential quality of accuracy; that can assist in minimizing the complex processing to determining the desired signal. Also allow for high reliable outcomes by reconstruction some of the earlier studies for instance in a sophisticated study [34], to calculate hemoglobin content in blood, where FFT method was used to remove the redundant parts of inaccurate PPG signal which already has its cons.

5. CONCLUSION

The achieved findings of amplitude fluctuations and FFT peak plots showed that the proposed approach is capable of indicating all kinds of effective noise caused by motion due to the similarity of influential sources for the PPG signal processing within ANC technique. Also proved that the traditional methods such 3-axes

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acceleration or an extra PPG sensor are not quite effective to provide the real induced noise because of the different source type for the first case and the difficulty of uniting screen room of skin subject, for the second instance. The outcomes of utilizing such method are to ensure the high accuracy and reliable measurements during diagnosis of pathological situations and reduce false alarms. In addition to reducing the expenses of the repeated examinations when the lack of reliability and economic exchange of energy compared to the aforementioned used methods where the first consists of three channels and the second includes a LED and detector. Practical application of this approach besides another comparison study among the linear correlations for the collected signals from CPD, MPD, and the acceleration as further evidence will be in our future work.

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