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Measurement of Heart Rate Variability with Optical Homodyne Detection Technique

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Abstract:
Abstract-The vibrations on the body surface specially chest wall and wrist are results of deformation of the heart. The pulse wave which is traveling through the body causes vibrations on skin surface. Any respiratory and cardio disorder affects the total chest wall mechanics. There is clinical usefulness of chest wall mechanics information for detection of any respiratory and heart disorder. The optical homodyne detection technique is used for measurement of frequency of modulated optical signal. It works on the principle of Michelson interferometer. An optical signal is split into two beams with beam splitter and combined after traveling equal path lengths. If the path difference between two orthogonal beams becomes zero, the phase difference between these beams becomes zero or constant. In optical homodyne technique, one of the two beams get reflected from a mirror which is subjected to vibration frequency of chest wall. After reflection, the optical signal gets modulated by frequency of vibration of mirror. These two optical signals form an interference pattern which contains the information of vibration frequency. Thin nano-dimensional optical reflectors are used on wrist & chest wall for this detection technique. The nano reflectors provide advantage of transferring of complete vibrations due to their negligible mass. Optical homodyne detection technique provides the accuracy of the order of 0.017 Hz for measurement heart rate variability. Vibrocardiogram (VCG) output for different heart rate values are compared with standard electrocardiogram (ECG) signal and measurement of variability is performed.

Keywords: *HRV, Homodyne, Interferometer, VCG, Lab VIEW*

I. Introduction

In Michelson interferometer, a beam of light from an optical source is divided into two parts of equal intensities by partial reflection and refraction. These beams travel in two mutually perpendicular direction and come together after reflection from plane mirrors. The beams overlap on each other and produce interference fringes. Fig.1shows the basic Michelson interferometer. One part of the split light beam is refracted in the direction of the static mirror M1 while the other part travels towards adjustable mirror M2. When both of the light beams are reflected from the mirrors, they are again combined in the same beam splitter and travel in the direction of the detector where the interference pattern is detected. The interference pattern depends on the difference of the path lengths$(L_1 - L_2)$ that the split beams have to travel [1].

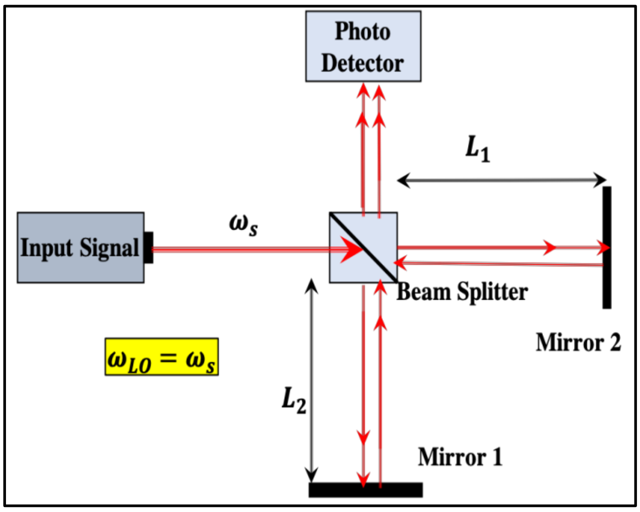

Figure 1: Basic self-mixing Michelson interferometer

By changing the position of the second mirror the interference pattern on the detector will change. By

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knowing the number of interferences fringes it is possible to derive the distance by which the second mirror was moved.

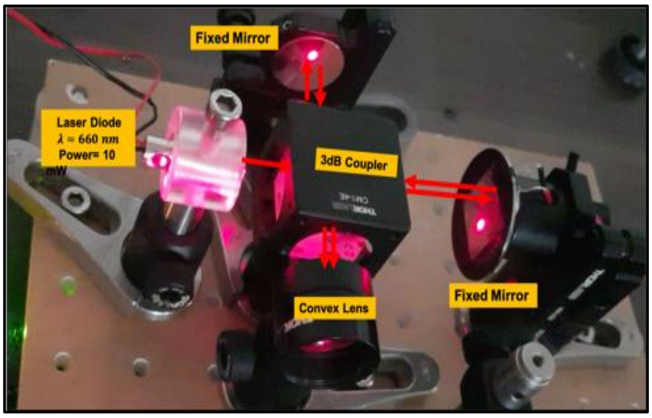

Figure 2: Setup for Michelson interferometer

A continuous wave laser source of wavelength 660 nm, optical power 10 mW and spectral width of 10 nm is used for construction of interferometer.When both beams travel equal distance ($L_1 = L_2$) , then total path difference becomes zero. The phase difference between two beams $\Delta\varphi$ is related to path difference by [2]

$$\Delta\varphi = \frac{2\pi}{\lambda}\Delta L \qquad (1)$$

Thus, for equal path length, the phase difference $\Delta\varphi$ is either zero or constant. Figure 3 shows the circular fringe pattern obtained from Michelson interferometer. The periodic fringe pattern of red and black shows constructive & destructive interference. The condition for constructive interference is givenby

$\Delta L = n\lambda$, for n = 0, 1, 2… (2)

The condition for destructive interference is given by

$\Delta L = (n + 1/2)\lambda$, for n = 0, 1, 2… (3)

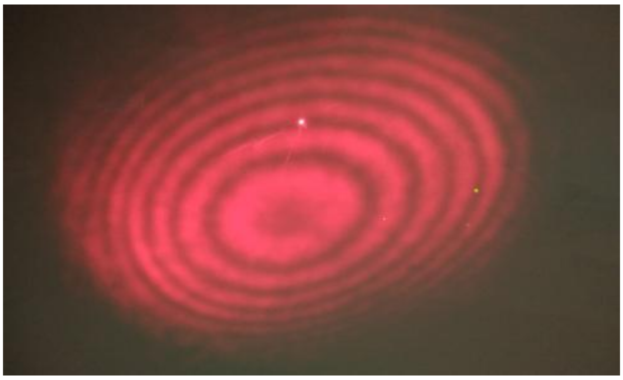

Figure 3: Fringe pattern with Maxima & Minima

II. Optical Homodyne detection technique

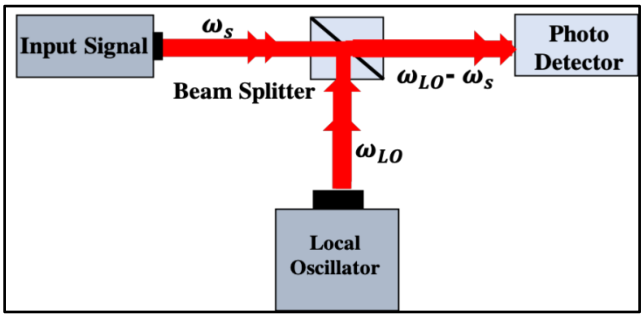

Figure 4: Optical Homodyne Technique

In coherent detection, receiver adds light to the received signal as part of the detection process. Figure 3 shows basic block diagram of optical homodyne detection [3, 4]. The optical signal is demodulated directly to the baseband. It requires a local oscillator whose frequency match the carrier signal and whose phase is locked to the incoming signal ($\omega_s = \omega_{LO}$).Information can be transmitted through amplitude, phase or frequency modulation. The self-mixing homodyne interferometer is shown in Figure 4. This setup has advantage of being insensitive towards fluctuations in frequency of laser source. In homodyne detection technique the local oscillator signal is provided by laser source itself.If there are fluctuations in the frequency of laser source, then both orthogonal beams will be subjected to same frequency fluctuations as that of laser source. Thus, optical homodyne technique is ideally suitable for measurement of velocity and frequency of any subject under test.

The optical homodyne technique for heart rate detection makes use of same type of frequency signal as shown in Figure 5. The laser diode signal with frequency f_0 is split in two orthogonal arms of interferometer by 3 dB beam splitter. The frequency of optical signal remains the same (f_0) in both orthogonal arms. In this case the local oscillator signal is provided by a fixed mirror M, which reflects back the signal whose frequency is f_0. The modulated optical signal is the optical bio-signal which is reflected from human test subject. Both local oscillator and modulated signal are obtained in two

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orthogonal arms of interferometer. The pulse frequency of human test subject is f_p.

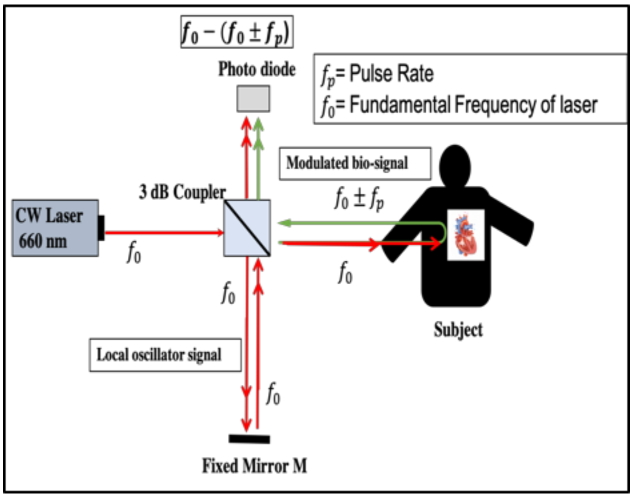

Figure 5: Optical homodyne setup with human subject

Optical signals travels in two orthogonal arms and gets combined at the same 3-dB splitter. In this case, in both arms of interferometer, optical signals travel the same path distance. Thus, the total path Thus, the total path difference in two orthogonal arms becomes zero. The zero-path difference of both orthogonal arms leads to zero phase difference between two optical signals. Therefore, frequency of carrier signal $f_0 \pm f_p$ ismatched to local oscillator signal f_0 and phase of both the beams are locked. Modulated bio signal is given by [5, 6]

$$E_s = A_s \text{Exp}\,[-j[2\pi(f_0 \pm f_p)t + \Phi_s]] \qquad (4)$$

Local oscillator signal is given by

$$E_{LO} = A_{LO}\,\text{Exp}\,[[-j[2\pi f_0 t + \Phi_{LO}] \qquad (5)$$

The output power of the photodetector

$$P(t) = P_s + P_{LO} + 2\sqrt{P_s P_{LO}}\cos(2\pi f_{IF} t + \phi) \; (6)$$

Power of modulated signal is given by

$$P_s = \frac{A_s^2}{2} (7)$$

Power of local oscillator signal is given by

$$P_{LO} = \frac{A_{LO}^2}{2} \; (8)$$

The intermediate frequency signal is given by f_{IF} ,which is difference of carrier signal and local oscillator signal frequency.

$$f_{IF} = (f_0 \pm f_p) - f_0 \; (9)$$

f_{IF} provides the heart frequency at photo detector

$$f_{IF} = f_p (10)$$

The overall phase shift observed at detector is difference of phase of modulating signal & local oscillator signal

$$\Phi = \Phi_s - \Phi_{LO} \; (11)$$

III. System Setup for HRV Measurement

The phase difference between both orthogonal beams is either zero or constant inside an interferometer. The fundamental optical frequency signal which is same as local oscillator signal (f_0) and modulated optical frequency signal which contains the information of heart frequency is shown in Figure 6.

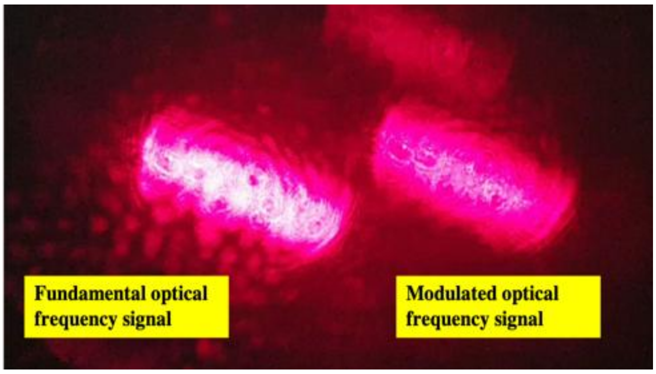

Figure 6: Fundamental & modulated light signal

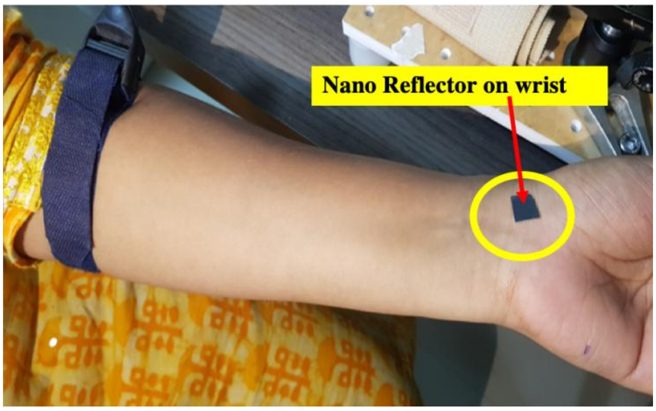

Figure 7: Test subject with nano-reflector on the wrist

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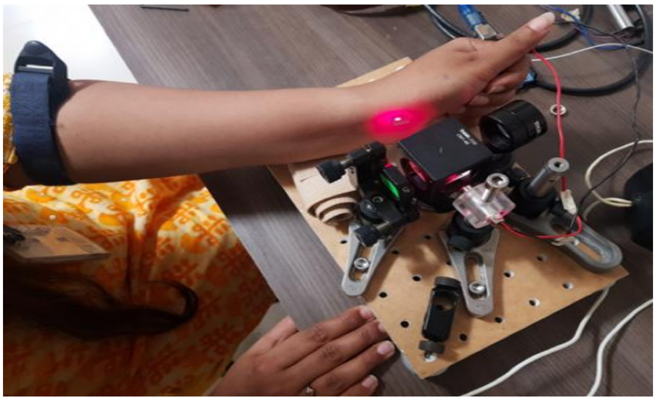

Figure 8: Optical homodyne setup with human subject

Figure 7 and Figure 8 shows the thin nano-reflector which is attached to wrist of human subject for measurement of pulse rate. One of the mirrors of homodyne system is replaced with reflector which is attached to human wrist. The nano-reflectors are fabricated on silicate substrate with gold sputtering technique. As nano-reflectors have negligible mass, they vibrate with the same frequency of human skin. After reflection from this reflector, the light signal gets modulated by exactly same frequency as that of human skin [7].

When laser signal is reflected from human subject, the waveform detected at photo receiver is called as Vibro-cardiogram (VCG). Figure 9, Figure 10, Figure 11 and Figure 12 represents the heart rate measurement for frequency 1 Hz, 1.1 Hz, 1.2 Hz and 1.3 Hz respectively. It is clear from these plots that VCG signal is an indicator of vibration generated due to muscular movements of chest wall. Simultaneously, ECG signal is obtained with contact type electrodes on the chest wall [8]

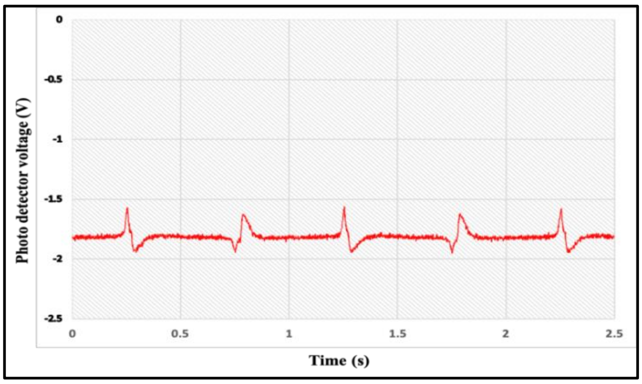

Figure 9: VCG for heart rate 60 beats per minute (1 Hz)

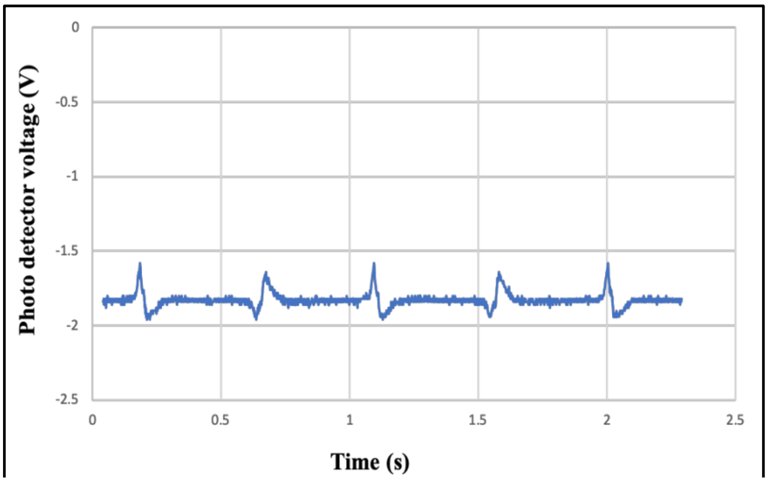

Figure 10: VCG for heart rate 66 beats per minute (1.1 Hz)

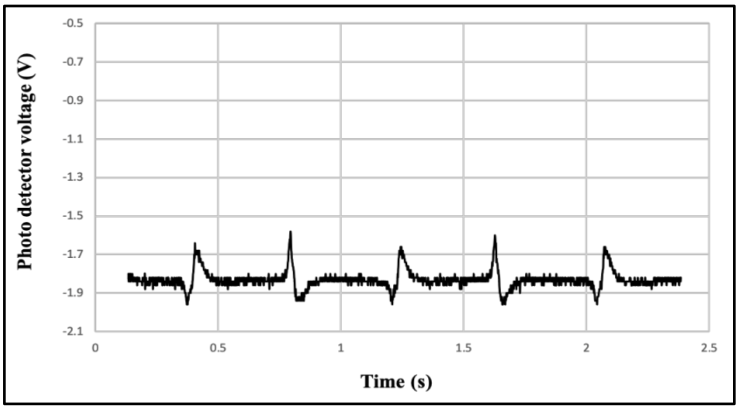

Figure 11: VCG for heart rate 72 beats per minute (1.2 Hz)

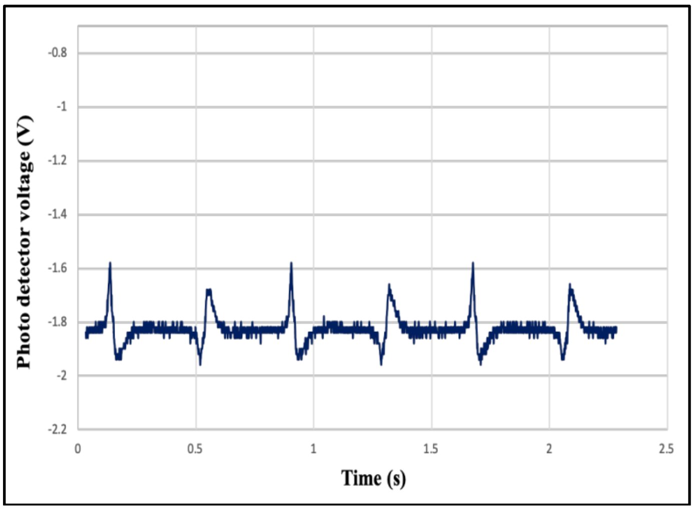

Figure 12: VCG for heart rate 78 beats per minute (1.3 Hz)

IV. Analysis

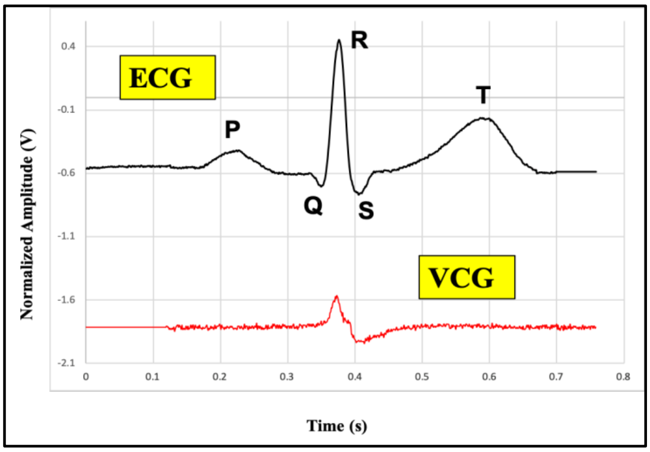

Figure 13: Single heartbeat ECG & VCG signal

ECG signal is obtained from attaching four contact sensors on the body. The optical homodyne technique is non-contact type technique. Figure 13 shows that single heartbeat VCG signal is obtained during same time duration of single heartbeat ECG signal. Heart rate variability (HRV) can be measuredbymeasuring the time duration betweenconsecutive periodic peak in the acquired plot. The peaks are known as V-peak in the plot as shown in Figure 14. The points V_1 and V_2 are obtained in co-ordination with Q, R and S wave of ECG [9, 10]. Thus points V_1 and V_2 can be used to characterize Q, R and S wave.

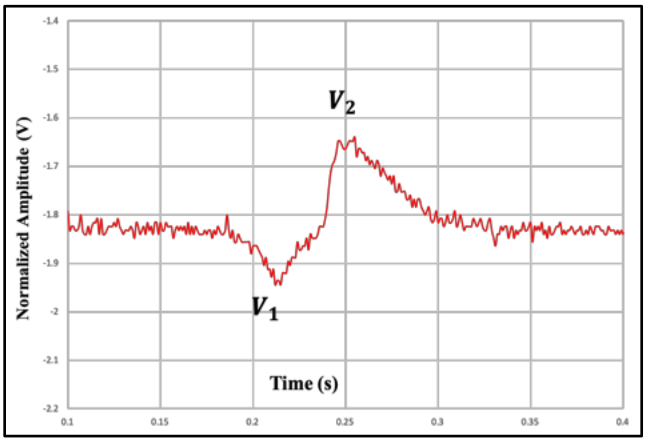

Figure 14: V-Peaks in VCG signal

V. Conclusion

In this research paper, Optical homodyne technique for measurement of HRV is demonstrated. It is an important sensing method for detection of biological signals and identification of muscular activities. Self-phase homodyne detection technique has advantage of being a contactless method. This technique is more important for patients with critical skin injuries. The precision accuracy of self-mixing homodyne technique is obtained as 0.017 Hz, that corresponds to 1 heartbeat signal in a minute.

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