Second International Conference on Emerging Trends in Engineering and Technology, ICETET-09

Heart Sound Abnormality Detection Using Short Time Fourier Transform and Continuous Wavelet Transform

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***Abstract*-This paper is concerned with the analysis of the first (S1) and second (S2) heart sound of the Phonocardiogram signal (PCG) using Short -Time Fourier Transform (STFT) and Continuous Wavelet Transform (CWT). The frequency content and time duration of S1 and S2 can be determined by the STFT without difficulties. The second heart sound S2 consists of two major components A2 and P2. The time delay between them is very important for the medical diagnosis. Experiments are performed on normal and pathological PCG signals. Frequency contents of S1 and S2 of PCG as well as time duration of them have been measured using STFT. Split between A2 and P2 have been measured using CWT.**

***Keywords*-** Heart Sounds, Short-time Fourier Transform, Continuous Wavelet Transform

I. INTRODUCTION

The mechanical activities of the heart during each cardiac cycle produce the sounds, which are called heart sounds. The factors involved in the production of heart sounds are as follow: (1) The movement of the blood through the chambers of the heart (2) The movements of cardiac muscle. (3) The movement of the valves of the heart. The heart sounds can be heard by placing the ear over the chest or by using a stethoscope or microphone. These sounds can also be recorded graphically [1, 2]. Human heart generates four sounds during its activity for one cardiac cycle. These sounds identified as S1, S2, S3 and S4 are not all audible [3].

A phonocardiogram (PCG) is a display of the heart sound signal showing that heart sounds and murmurs can provide useful information to the physician by complementing cardiac auscultation. The major PCG clinical drawback is that it does not present information on frequency of heart sounds and their components [4, 9]. Heart sound analysis by auscultation is still insufficient to diagnose some heart diseases. It does not enable the analyst to obtain both qualitative and quantitative characteristics of the PCG signals. In addition to the first and second sounds, abnormal heart sounds may contain murmurs and aberrations caused by different pathological conditions of the cardiovascular system. Moreover, in studying the physical characteristics of heart sounds and human hearing, it is seen that the human ear is poorly suited for cardiac auscultation. Therefore, clinic capabilities to diagnose heart sounds are limited. The characteristics of the PCG signal and other features such as location of S1 and S2, the number of components for each sound, their frequency content, their time interval, all can be measured more accurately by digital signal processing techniques. The Short-time Fourier transform (STFT) can provide the frequency and time duration of each heart sounds [3]. Discrete Wavelet Transform (DWT) is used for denoising and finding of best split of A2 and P2 in the band [6, 7]. However the time duration between split can not be measured using STFT and DWT. The Continuous Wavelet Transform (CWT) provides the duration between the split of A2 and P2. Since heart sounds exhibit marked changes with time and frequency, they are therefore classified as non-stationary signals. To understand the exact features of such signals, it is thus important to study their time-frequency characteristics. In this paper the STFT have been used to determine the frequency and time duration of S1 and S2 heart sound. The CWT is used to measure time delay between the component A2 and P2 for the second heart sound for the normal and pathological PCG.

This paper is organized as follows: Section II presents the processing of heart sounds using STFT and CWT. Experimental analysis of normal and various pathological heart sounds using above techniques have been presented in Section III. Finally the conclusions have been given in Section IV.

II. Processing of Heart Sounds

2.1 Short -Time Fourier Transform,

The STFT is based on the usual Fourier Transform (FT). The problem with Fourier transform was that it does not work for non-stationary signals. Now, we treat some portion of a non-stationary signal as stationary. If this region where the signal can be assumed to be stationary is too small, then we look at that signal through narrow window, narrow enough that the portion of the signal seen from the window is indeed stationary. This approach ended up with a revised version of the Fourier transform, called Short Time Fourier Transform (STFT). Thus, instead of the usual FT expression, we use the time-frequency expression as [3, 10]:

$$STFT(t', f) = \int_t [x(t)w^*(t-t')]e^{-2\pi ft}dt, \qquad (1)$$

where $x(t)$ is the PCG signal, $w(t)$ is the time window function, * is the complex conjugate, t' is time and f is frequency. The magnitude spectrum of STFT or spectrogram approach consists of subdividing the signal into a number of small overlapping records. Each sub-record is assumed to be stationary. All sub-records are multiplied with an appropriate window in order to reduce the effect of leakage due to the time truncation of the signal and then a Fast Fourier Transform (FFT) algorithm is applied to each segment.

The frequency resolution is equal to the inverse of the analyzing window duration. So it is very problematic to ensure a good stationarity with an acceptable frequency resolution because of this inverse proportionality between them. If the signal does not contain rapid changes in each sub-record, the spectrogram with a short duration analyzing window can describe the spectral components of the whole signal. To deal with these limitations, it is recommended to keep the duration of the sliding window as short as possible to ensure the stability criterion [3, 8]. Unfortunately, this will reduce the frequency resolution of the spectrogram. Therefore a time-frequency trade-off have been taken into account.

2.2 Continuous Wavelet Transform

Continuous Wavelet transform is the alternative approach to the STFT [10]. Wavelet Transform (WT) has become well known as useful tools for various signal processing applications because of its good time-frequency resolution. CWT is best suited for signal analysis. Wavelet transform consist of computing coefficients that are inner products of the signal $x(t)$ and a family of “wavelets”.

Continuous wavelet transform can be formally written as:

$$\Psi_x^{\psi}(\tau, s) = \int x(t)\psi^{*}_{s,\tau}(t)dt, \tag{2}$$

where $\psi_{(s,\tau)}(t)$ is called wavelet function. The variables s and τ are scale and translation parameter.

The wavelets are generated from a single basic wavelet $\psi(t)$ (that satisfies the following properties), the so-called mother wavelet, by scaling and translation:

$$\psi_{(s,\tau)}(t) = \frac{1}{\sqrt{|s|}}\psi\left(\frac{t-\tau}{s}\right), \tag{3}$$

where, s is the scale factor, τ is the translation factor and the factor $s^{-1/2}$ is used for energy normalization across the different scales.

Wavelet function in CWT should satisfy the following properties:

Admissibility Condition:

$$C_{\psi} = \int_{0}^{\infty}\left|\frac{\Psi(\omega)}{\omega}\right| d(\omega) < \infty, \tag{4}$$

where $\Psi(\omega)$ is the FT of $\psi(t)$. This condition ensures that $\Psi(\omega)$ goes to zero as quickly as $\omega \rightarrow 0$.

Zero average: It is normalized which means $\|\psi\| = 1$ and is centered in the neighborhood of $t = 0$ i.e.

$$\int_{-\infty}^{\infty} \psi(t)dt = 0. \tag{5}$$

Unit energy: Wavelet function should have unit energy.

$$\int_{-\infty}^{\infty} |\psi(t)|^2 dt = 1. \tag{6}$$

In short wavelets have zero average, unit energy and have fast decay. This means that $\psi(t)$ is wave for short duration and hence the name wavelet. If $\psi(t)$ is a real wavelet, then the resulting $\Psi_x(s,\tau)$ is called a real WT, measures the variation of $x(t)$ in a neighborhood of τ whose size is proportional to scale s. A real WT maintains an energy conservation principle, as long as the wavelet satisfies admissibility condition [10].

III. Results and Discussion

Normal and Pathological PCG signals were analysed using STFT and CWT techniques. PCG signals were recorded using electronic stethoscope. The sampling rate used was 8000 samples/s. Various pathological conditions such as aortic stenosis, pulmonic stenosis, atrial septal defect were consider for analysis.

3.1 Short Time Fourier Transform Analysis of the PCG

STFT algorithm is applied on the PCG signal for both normal and pathological to determine the frequency components present and the time duration measurement of S1 and S2. To avoid the blocking effect while using STFT, hamming window of length 256 is used in all the experimentation.

Segmentation of the PCG signal is done for one cardiac cycle. This segment carries the maximum information of S1 and S2.

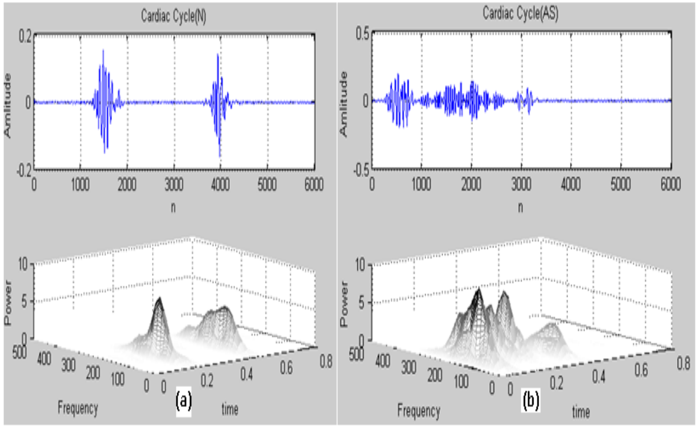

Fig.1 Spectrogram of the PCG Signal (a) Normal (b) Aortic Stenosis

The application of the STFT on heart sounds cardiac cycle after their segmentation shows the frequency components and time duration of each heart sound.

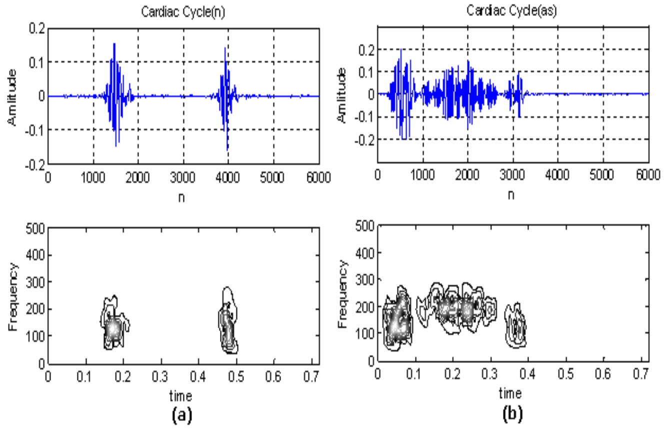

Fig.2 Contour plot of the (a) Normal (b) Aortic Stenosis signal Spectrogram

Fig.1 (a) and Fig.2 (a) shows the spectrogram and contour plot for normal cardiac cycle respectively. Fig.1 (b) and Fig.2 (b) shows the spectrogram and contour plot for aortic Stenosis cardiac cycle respectively. As shown in Fig.1 and Fig.2, heart sounds S1 and S2 are clearly localized in time and frequency domains. Here in case of normal heart sound signal S1 has energy localized in the range of 100 Hz to 150 Hz which is emphasize in contour plot and S2 has energy localize in the range of 50 Hz to 250 Hz which is uniformly distributed. In case of aortic stenosis S1 has energy localized in the range of 50 Hz to 280 Hz and also has more number of peaks. This is emphasize in contour plot. S2 has nonuniform distribution of energy which is localize in the range of 50 Hz to 220 Hz and has more time duration of sound.

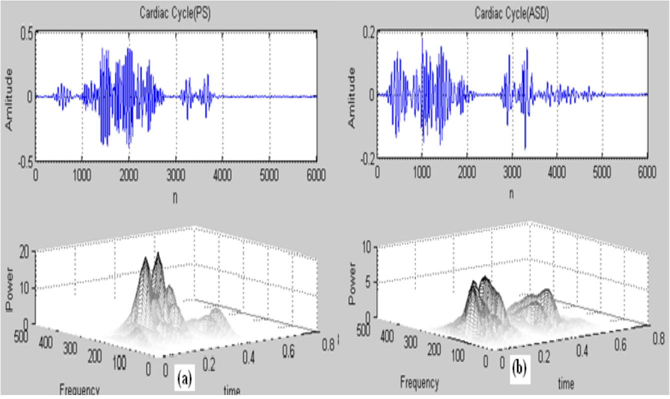

Fig.3 Spectrogram of the PCG Signal (a) Pulmonic (b) Atrial Septal Defect

Fig.3 shows spectrogram of Pulmonic and atrial septal defect and Fig.4 shows their contour plots. In case of pulmonic stenosis, energy of S1 was localized in the range of 80 Hz to 280 Hz but strength of S1 is suppressed as compared to abnormality. It is also observed that the S2 and abnormality have more number of peaks. These have been clearly shown in Fig.3 (a). In case of atrial septal defect (refer Fig.3 (b) and Fig.4 (b)), energy is localized in range 50 Hz -265 Hz. Also more number of peaks and time duration were seen in S1 and S2.

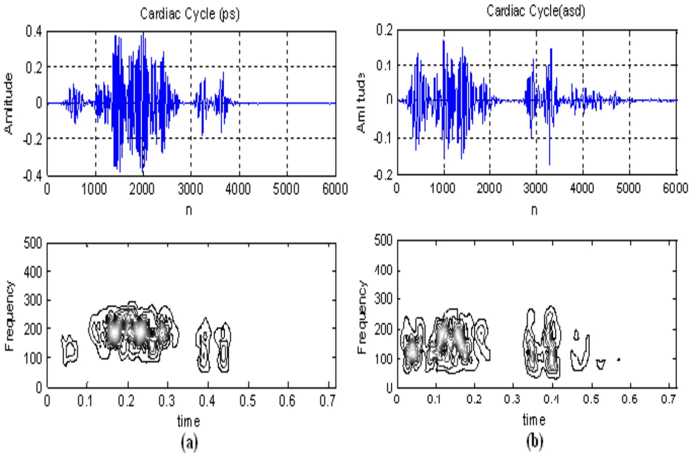

Fig.4 Contour plot of the (a) Pulmonic (b) Atrial Septal Defect

From above experimental result of the STFT it can be concluded that:

- For the normal heart, S1 includes a single frequency spectral component of energy and the duration of the sound is less in the range of 0.04sec - 0.15sec .On the other hand for the abnormal heart, the frequency spectrum depicts more number of energy components and the duration of the sound is larger than the normal one.
- For the normal heart, S2 represents a uniform frequency spectral component of energy and the duration of the sound is less in the range of 0.03sec-0.12sec .On the other hand for the abnormal heart, the frequency spectrum of energy components are not distributed uniformly and the duration of the sound is also prolonged.
- The magnitude of the energy components of normal heart S1 is higher than that of S2. But in case of pathological, there are more chances of S2 sound energy components to have larger magnitude than that of S1.

Table 1 shows the frequency ranges of S1 and S2 and their time durations obtained using STFT.

The application of the STFT on heart sounds S1 and S2 after their separation or identification shows the basic frequency spectral components and their time duration for which the sound is present but time-frequency is having inverse relation. Hence frequency resolution is less if we take small window and time resolution is less if we take large window. To overcome this limitation CWT is used.

Table.1: Measure of frequency and time duration of various analyzed signal using STFT

Type of Signals	First Heart Sound Frequency (Hz)	First Heart Sound Time(sec)	Second Heart Sound Frequency (Hz)	Second Heart Sound Time (sec)
Normal	100-150Hz	0.069	50-250 Hz	0.042
Aortic Stenosis	50-280Hz	0.292	50-220Hz	0.048
Pulmonic Stenosis	80-280Hz	0.282	50-250Hz	0.073
Atrial Septal Defect	50-265Hz	0.22	50-280Hz	0.085

3.2 Continuous Wavelet Transform Analysis of the PCG

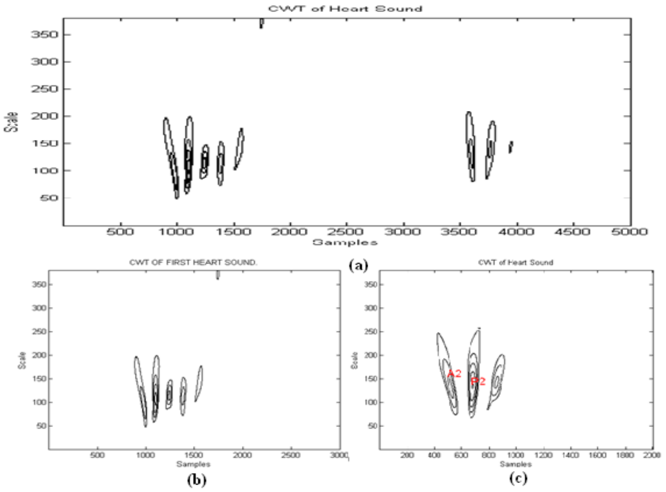

Fig.5 Coefficient of the CWT for the Normal Heart sound (a) One cardiac cycle (b) sound S1 (c) sound S2

An algorithm of the CWT was applied to analyse the PCG signal of a normal cardiac cycle illustrated in Fig.1 (a) and Fig.5 (a). The two heart sounds were clearly shown in dark colour in Fig.5 (a). There was space of 2400 samples corresponding to 0.3 seconds. The CWT of S1 and S2 were also displayed separately in Fig.5 (b) and Fig.5 (c) respectively. As it is shown in Fig.5(c), the sound S2 have higher frequency content than that of the S1. This is expected since the amount of blood present in the cardiac chambers is smaller [1]. The spectrum of S1 is clearly resolved in time in Fig.5 (b) into four major components. The spectrum of the sound S2 is resolved (in time Fig.5 (c)) into two major's components A2 and P2. The time delay between A2 and P2 can be easily measured (from Fig.5 (c)) using wavelet coefficients. This delay is measured to be 24ms. It was smaller than the 30ms as seen in the normal conditions of the PCG signal. In pathological condition this time difference is widen. The wavelet transform allows measurement and determination of this time difference and thus allows a diagnostic process regarding this important parameter to be produced. Here the one normal and three pathological cases were considered i) aortic stenosis ii) pulmonic stenosis and iii) atrial septal defect as shown in Fig.6, Fig.7, and Fig.8 respectively.

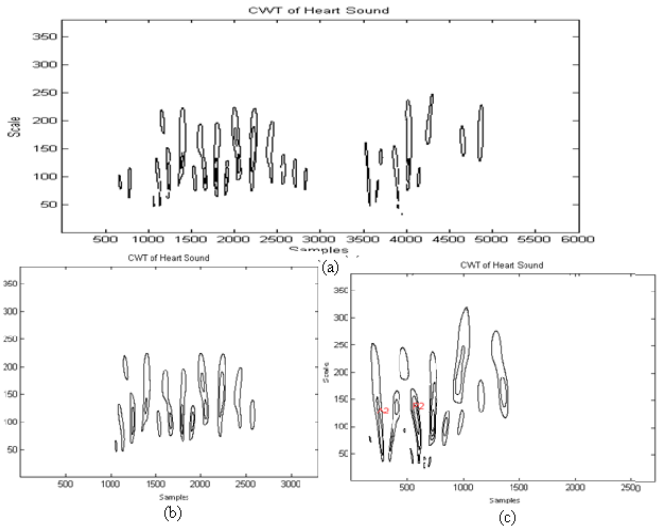

Fig.6 Coefficient of the CWT for the Aortic Stenosis (a) One cardiac cycle (b) sound S1 (c) sound S2

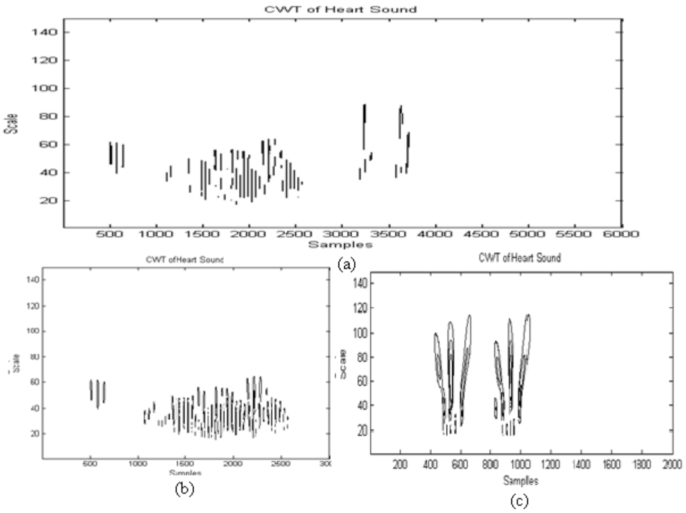

Fig.7 Coefficient of the CWT for the Pulmonic Stenosis (a) One cardiac cycle (b) sound S1 (c) sound S2

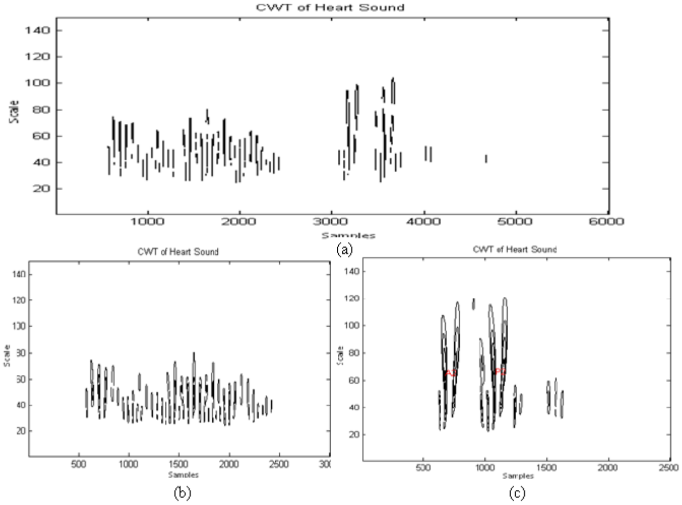

Fig.8 Coefficient of the CWT for the Atrial Septal Defect (a) One cardiac cycle (b) sound S1 (c) sound S2

3.3 Measure of the Split S2

As specified in above sub-section that A2 and P2 of the S2 produced due closer of aortic and Pulmonic valve, its time difference is very important for diagnosis of heart valves. The time difference between these two components in case of normal case is less than 30ms. But in abnormal case it may be become wide [8]. In normal case the dominant components were clearly seen representing A2 and P2 using CWT and its time difference 24ms. This is less than 30ms, while in pathological aortic stenosis case as shown in Fig.6 has more frequency components. Here time duration between A2 and P2 is 43ms. Pulmonic stenosis shown in Fig.7 has more frequency component and time duration between A2 and P2 was 48ms. Atrial septal defect shown in Fig.8 also has more frequency component and time duration between A2 and P2 was 50ms. Hence from above three cases the time difference between A2 and P2 is more than 30ms due to abnormality.

From above experimental results of the CWT it can be concluded that:

- In S2 two frequency components have been produced due to closer of the aortic (A2) and Pulmonic (P2) valve and were clearly detected using CWT.
- For normal heart the time interval between A2 and P2 is less than the 30ms and for pathological case the time interval between A2 and P2 is larger than the 30ms and is measured easily.

Table 2 shows the experimental measurements of split time for various normal and pathological conditions.

Table2: Split time for normal and pathological conditions

Type of Signals	Normal	Aortic Stenosis	Pulmonic Stenosis	Atrial Septal Defect
Split(ms)	24	43	48	50

IV. CONCLUSION

Short Time Fourier Transform (STFT) have been used to determine the frequency component and the time duration of each heart sound. With STFT it is impossible to determine the time duration between A2 and P2 which plays vital role in diagnosis of the PCG signal. This drawback of the STFT is over come using CWT. The time delays between A2 and P2 have been measured using CWT. It is observed that the time delay between A2 and P2 is less than 30ms for normal case and it is greater than 30ms for pathological cases. With the developed Software, it is easily possible to identify whether the person is normal or abnormal with valves condition.

It can be a good tool to help doctors to take decision for diagnosis of various diseases related with heart valves.

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