

Real Time Applications of Wavelet Transforms to Monitor Cardiac Signal

D.Mandal¹, I .SahaMisra²

Department of Electronics and Communication Engg, Heritage Institute of Technology, Kolkata, India¹

Department of Electronics and Tele- Communication Engg, Jadavpur University, Kolkata, India²

ABSTRACT: In this work we have proposed some algorithm and applications of wavelet transform to the cardiac signal, especially to the heart sound signal for monitoring the cardiac disorder. Heart sound signals are normally weak signal. It is tough to detect the heart sound signals using common sensor. In this work we have applied some DSP based algorithm and DSP processor (TMS320C6713) to detect the heart sound signal. Then we have applied the algorithms and wavelet transform to the heart sound signal. Before applying the wavelet transform to the heart sound signal, we have discussed about the wavelet and wavelet transform briefly. To proceed to the work first of all we have selected some special type of analog signal and we have chosen some typical wavelet transform to the signals. The results have been noticed and accordingly we have made some algorithm to fulfil our objectives. Time domain and frequency domain analysis have been carried out. Haar, Daubechies, Symlet and Coiflet wavelets have been utilized. In this work we have studied more than 20 heart sound signal.

KEYWORDS: Wavelet, heart sound, heart bit, cardiac disorder.

1. INTRODUCTION

In the last 10 years a lot of improvement has been seen in the field of biomedical science and presently biomedical signal processing is taking leading role to detect different types of mechanical disorder of different body parts or limbs like lungs, heart, kidney etc, due to different body parts failure or affected by some disease. As we know that wavelet transform can give the best result to analyze a signal in time and in frequency domain, in this work we are going to apply this to the cardiac signal. In case of the biomedical signal different frequencies occur at different instant of time therefore it is difficult to analyze these signals using traditional Fourier transform or the short time Fourier transform. In [1] the Fourier transform based ECG signal analysis has been shown. The power spectral density of the ECG signal shows the presence of noise. But which wave of the ECG (out of P, Q, R and S) is affected, it is not clear from the spectra. In [2] the Fourier transforms and short time

Fourier transforms has been applied to the heart sound signal. Here the problem is that it is difficult to identify which heart sound component like S1, S2 or S3 is consist of a particular frequency. It is only possible to know which frequencies are present for all the heart sound components. As a result further analysis of S1, S2 or S3 is becoming difficult. It is known to us that different heart sound components occur at different time interval; therefore we need some technique so that we get the time- frequency analysis of a signal. Heart bit rate detection technique has been discussed in [3]. But here the detail of a particular bit was not shown. In [4], [5] and [6] detection of different ECG waves like P, Q, R and S have been shown but details of the frequency domain analysis were not shown. In [7] application of digital filter to the heart sound signal has been applied. But due to proper selection of the cut-off frequencies results are not better. The concept of digital filter bank has been introduced in [8]. It shows better result but the process is lengthy. In some works [8],[9],and [10] continuous wavelet transform based analysis are shown. In this case comparatively better result was achieved. Because of the fact that wavelet transform based analysis can give the details idea of time-frequency resolution of a signal they have got a better result. In this work we have applied continuous wavelet transform to the heart sound signal. Different wavelet transforms based algorithm has been applied. The results have been compared. The whole work is presented as follows: In Section II we have discussed about wavelet transform and Fourier transforms and how we can apply this to the cardiac signals. The comparison of wavelet

International Journal of Innovative Research in Science, Engineering and Technology

(An ISO 3297: 2007 Certified Organization)

Vol. 5, Special Issue 13, October 2016

transform and Fourier has also been discussed. In Section III heart sound detection technique has been introduced. In Section IV we have applied wavelet transform based algorithms to the heart sound signals. Results have been discussed in Section V.

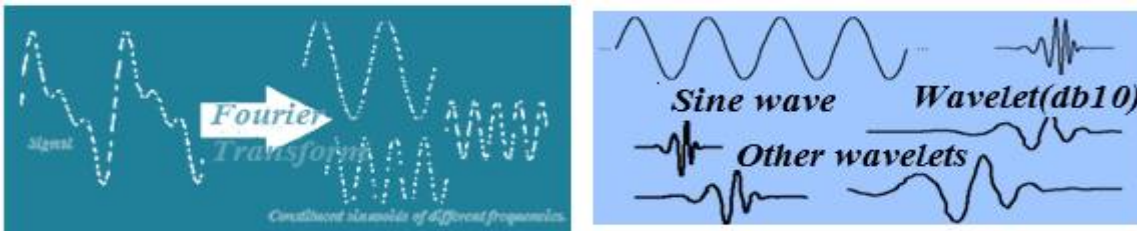


Fig.1. Example of Fourier transforms and wavelets.

II. INTRODUCTION TO WAVELET TRANSFORM AND FOURIER RANSFORM

A. FOURIER TRANSFORM

Mathematical expression: $f(\omega) = \int_{-\infty}^{\infty} f(t) e^{-j\omega t} dt$ 1 Meaning of the Fourier transform is that the sum over all time of the signal $f(t)$ multiplied by a complex exponential, and the result is the Fourier coefficients $F(\omega)$. The complex exponentials are nothing but the constituent sinusoids of different frequencies. These Fourier series coefficients are the strength of the constituent sinusoids and all these sinusoids help to reconstruct the original signal. Here the question is: why should we break the original signal into its constituent sinusoids of different frequencies? The Fourier series coefficients show the strength of constituent sinusoids, more strength meaning is that more contribution to reconstruct the original signal. Therefore it is easy to identify which constituent sinusoids of different frequencies are important and what will be the bandwidth of the signal. Once the bandwidth and range of frequencies are known it is easy to analyze the signal through a proper filter or other system.

B. WAVELETS

A wavelet is a waveform of effectively limited duration that has an average value of zero. Examples of wavelets and Fourier transform have been shown in figure 1.

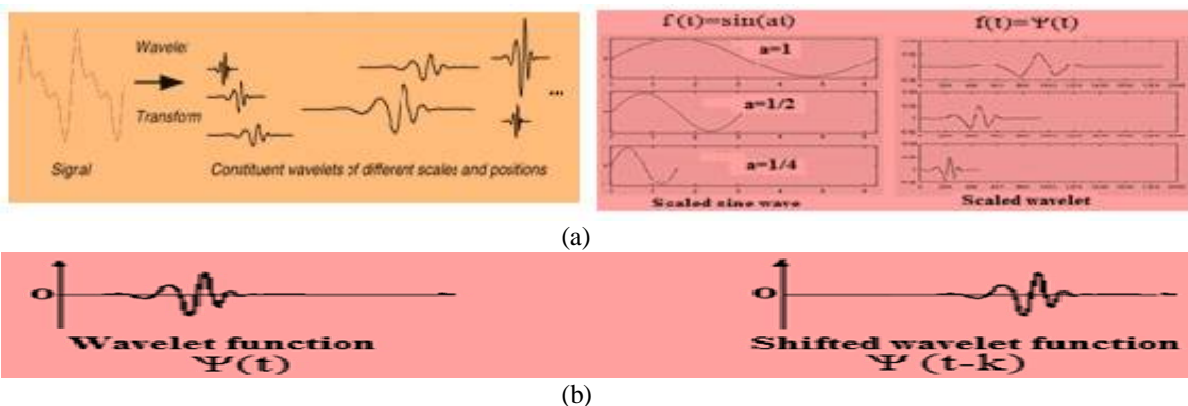


Fig.2. Examples of(a) scaled sine wave and(b) scaled wavelet

Wavelets are short time localized waves with zero integral values. It can be shifted or scaled. Scaled sine wave and wavelets are shown in figures2. Mathematical Expression of scaled and shifted wavelet function: $\Psi_{a,b}(x) = 1/\sqrt{a} \Psi_{a,b}((x-b)/a)$2 Here the wavelet function is $\Psi(x)$ and it is scaled with the scaled factor 'a' and shifted by 'b'.

International Journal of Innovative Research in Science, Engineering and Technology

(An ISO 3297: 2007 Certified Organization)

Vol. 5, Special Issue 13, October 2016

C) CONTINUOUS WAVELET TRANSFORM

The CWT is the sum over all time of the signal, multiplied by scaled and shifted versions of the wavelet function and the result of the CWT are wavelet coefficients [11]-[14]. Multiplying each coefficient by the appropriately scaled and shifted wavelet yields the constituent wavelet of the original signal. What is actually done in case of continuous wavelet transform? The following steps are required to perform the wavelet transform operation: Step1: Take a wavelet and compare it to a section at the start of the original signal. It is shown in figure 3.

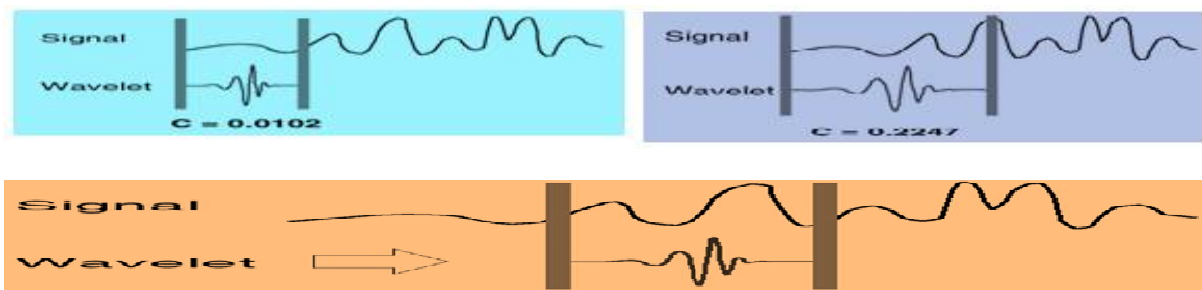


Fig.3. Example of wavelet transforms. 'C' represents the similarity between the wavelet and a section of the signal whose wavelet transform will be taken. Higher values of 'C' show more similarities.

Step2: Calculate a number, C, that represents how closely correlated the wavelet is with this section of the signal. The higher C is the more similarity. Step3: The wavelet is shifted to the right and then steps 1-2 are repeated until the whole signal is covered. Figure 7 and 8 represents step 3 and 4. Step4: The wavelet is scaled (stretched or compressed) and steps 1-3 are repeated. What is the result? After the whole process we are getting a number of wavelet coefficient 'C' that shows the similarity between the shifted and scaled version of the wavelet and the section of the original signal. Higher values of the 'C' indicate more similarity. What happens if 'C' gives the maximum similarity? Maximum similarity means the shifted and scaled version of the wavelet is similar to a particular section of the original signal which can construct the constituent wavelet of the original signal and ultimately we can represent the original signal with the help of all the constituent wavelets.

D. ADVANTAGES OF WAVELET TRANSFORM

With the help of the Fourier transform we get a number of constituent sinusoids of different frequencies which can represent the original signal. In the same way in case of wavelet transform we get a number of constituent wavelets which can represent the original signal. The advantages of wavelet transform are that we can scale the wavelet- means we can change the frequency of a particular constituent wavelet, high scale means low frequency and low scale means high frequency. Therefore we will apply high scaled for the low frequency signal and vice-a- versa. But in case of Fourier transform we cannot change the frequency of the constituent sinusoids. Another point is that we can select a particular section of the signal in time domain with the help of shifting the wavelet. This helps to know which frequencies are present in a particular time interval because we know the frequency of the shifted wavelet. This is not possible in case of Fourier transform at all.

III DETECTION OF HEART SOUND

Heart sounds are normally very weak signals. Normal microphones or other sensors are used to convert heart sound to electrical signal [15]

In this present work a stethoscope receives the heart sound and it is fed to a microphone. Next it is processed through an amplifier circuit and an analog low pass filter to remove some high frequencies noise. For further processing a DSP KIT is incorporated. Algorithm1 represents the whole process which is written in C. It detects the analog heart sound

International Journal of Innovative Research in Science, Engineering and Technology

(An ISO 3297: 2007 Certified Organization)

Vol. 5, Special Issue 13, October 2016

signal from the analog filter circuit. The CODEC which is inbuilt in the DSP KIT convert the analog heart sound signal to digital signal. Now the DSP processor uses the digital filters and windows for further processing of the signal. After processing, the results are sent to the PC through the CODEC. Data save option of this kit provide a wonderful job to save the digital data in PC. After getting the data in PC MATLAB software has been appointed to get the pure cardiac cycle and other results related to heart. Block diagram and the actual circuit are shown in the following figures. Figure 4 represents a heart sound signal. A block diagram of the experimental setup is illustrated in figure 5.

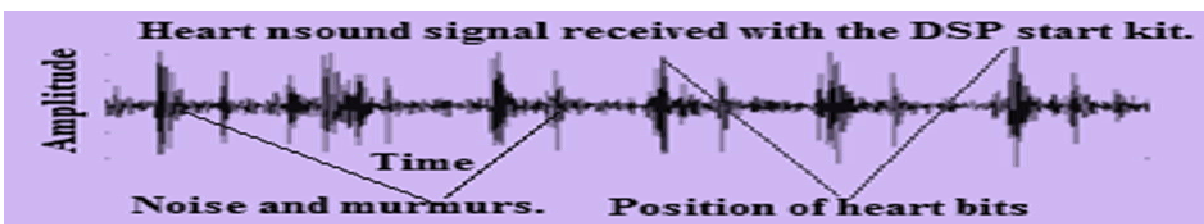


Fig.4. Example of heart sound signal received by our system.

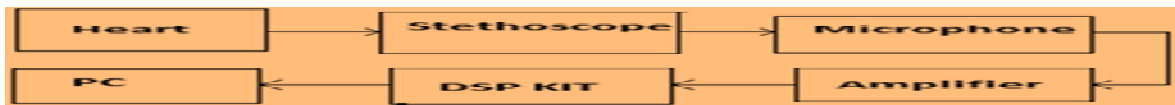


Fig.5. Block diagram of the experimental setup.

IV. APPLICATION OF WAVELET TRANSFORM TO THE HEART SOUND SIGNAL

A) Application of haar wavelet transform to the continuous time signal

In [18] it is shown that Haar continuous wavelet is defined by
$$\psi(t) = \begin{cases} 1, & -\frac{1}{2} \leq t \leq 0 \\ -1, & 0 \leq t \leq \frac{1}{2} \\ 0 & \text{otherwise} \end{cases} \dots (3)$$

And the scaled and shifted haar wavelet is given by $\psi_{a,b}(x) = \frac{1}{\sqrt{a}} \psi_{a,b}((x-b)/a) \dots \dots \dots 2.$

Wavelet transform co-efficient are calculated using $C = X(a,b) = \int_{-\infty}^{\infty} x(t) \psi_{a,b}(t) dt \dots \dots \dots (4)$ $a \in$

$R^+, b \in R$, The original signal can be reconstructed By $x(t) = \frac{1}{C_{\psi}} \int_{a \in R^+} \int_{b \in R} X(a,b) \psi_{a,b}(t) \frac{db da}{a^2} \dots \dots 5$
 $a \in R^+, b \in R$,

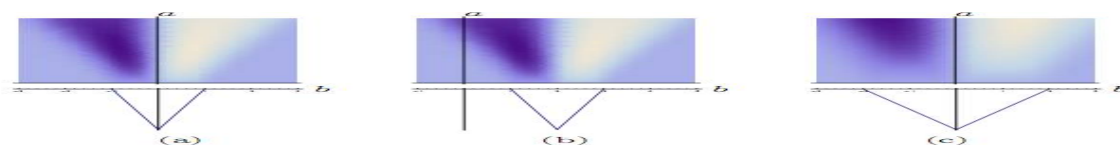


Figure.6.Examples of Haar wavelet transforms a) The Haar wavelet transform of an example function $x(t)$ (hat function). (b) Illustration of the shift-in-time property for $x(t-2)$. (c) Illustration of the scaling-in-Time property for $x(t/2)$.

B). Continuous wavelet transforms to detect heart bit rate.

As we know that heart sound signals are non-stationary signal, the frequencies may change time to time. It also happens that our heart normally produces heart bit at an equal interval, but some time it is irregular, as a result some missing pulse may occur. Therefore some discontinuities may occur due to this missing pulse which is known as syno-bradicadiy [17] . So for the proper analysis of heart sound we should detect when the frequencies are changing and

International Journal of Innovative Research in Science, Engineering and Technology

(An ISO 3297: 2007 Certified Organization)

Vol. 5, Special Issue 13, October 2016

where the discontinuities are occurring. Continuous wavelet transforms can help in this matter. We will take some examples on this matter and then we will apply this to the heart sound signal.

Let us take the following signals as given in figure 7. It represents some impulses. The position of the pulses is as follows: (i) one pulse at 500 and three pulses at 200,500 and 800. In (ii) a unit step signal which is zero from 400 to 500.

Next we will see what happens if we apply wavelet transform to the first signal that is the unit impulse situated at 500. Two wavelet Haar and coif have been applied. The results have been shown in the following figures.

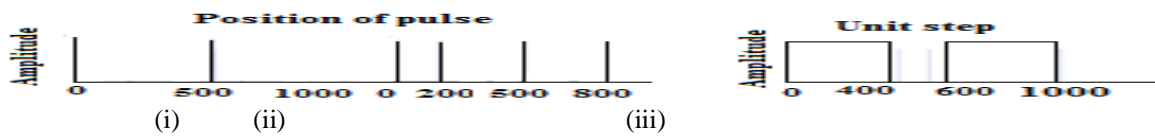


Fig.7. Shows the position of pulses at different time. i) Position of pulses. ii) Unit step signal. It is zero from 400 to 600.

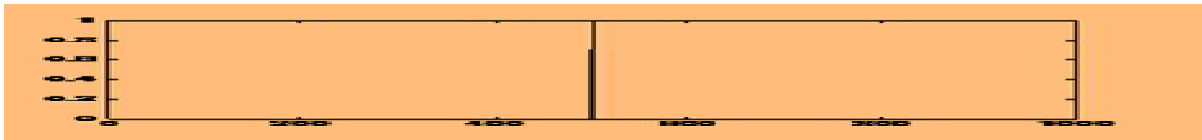


Fig.8. Unit impulse situated at 500.

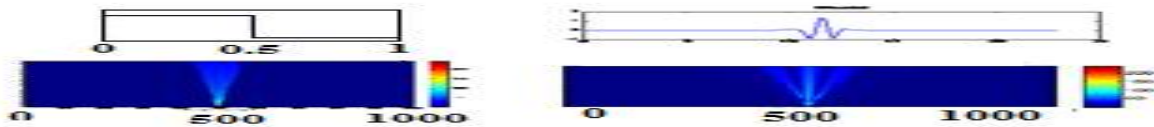


Fig.9. Results of wavelet transform. It shows that at position of pulse the wavelet co-efficient are high. The colour bar represents the values of wavelet co-efficient. Red colour indicates maximum and blue indicates minimum value.

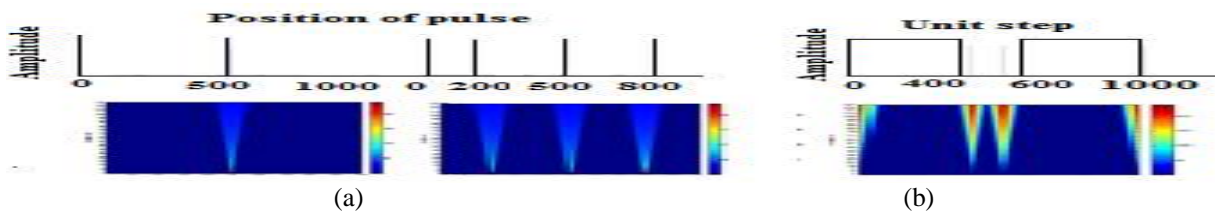


Fig.10.(a).It shows the position of pulses are at 500 ,200,600 and 8000 and their corresponding with their co-efficient 'C'. (b)it shows the discontinuities of unit step signal.

Now we will apply the wavelet transform to all the signals. We are selecting haar wavelet. The absolute values of wavelet transform co-efficient C with scale $a=1, 2, 3 \dots$ up to 128 are plotted in the same figure10.

From figure 10 it is clear that the co-efficient are higher at the position of the pulses for (a) and (b). It indicates that whenever there is a change in the signal pattern wavelet co-efficient are changing abruptly. For the signal (a) it is low or zero except the position of the pulses, accordingly wavelet co-efficient are very high at that points. In the same way for signal (b) it is one except the interval 400 to 600 and accordingly we are getting different wavelet co-efficient at that interval. Now the question is: why is it happening? If we look at the wavelet, we see that it is 1 for the interval of 0 to 0.5 and it is 0 for the interval 0.5 to 1. As we know that the wavelet co-efficient are the similarity between the signal and the wavelet so here the Haar wavelet is getting some similarity with the pulse but there is no similarity with zero or one. That is reflected in figure (10). Now the question is: how does this help to analyze the heart sound signal?

As we know that heart bits are produced at an equal interval. In most of the cases 72 bits (average) are produced in a minute. Each and every bit produces some sound that is known as heart sound. Therefore we can represent the heart sound signal as a train of weighted impulses where there will be 72 weighted impulses in a minute or during 60 seconds. Now using the wavelet transform we can easily detect the position of each pulses corresponding to each heart

International Journal of Innovative Research in Science, Engineering and Technology

(An ISO 3297: 2007 Certified Organization)

Vol. 5, Special Issue 13, October 2016

bit. It is also possible to detect the missing pulse if there is any. In figure (11) the heart sound signal and position of heart bits are shown. In the first part of figure (11) the heart sound signal with some noise has been shown. In the second and third part the wavelet transform co-efficient has been shown after applying the wavelet transform. In the second part the wavelet transform co-efficient have been considered without taking any threshold values whether in the third part some threshold values have been considered. From the figure it is clear that the wavelet co-efficient are high at the position of a pulse. Here we have found some irregular co-efficient whose values are comparatively high. This is due to the sound signal.

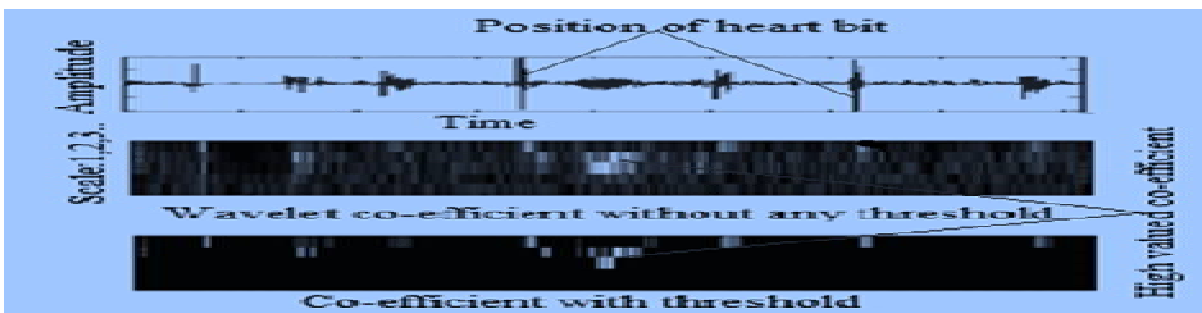


Fig.11. : Heart sound signal. Second and wavelet co-efficient indicate the positions of pulses. Higher values of co-efficient indicate the position of the pulse.

C). Continuous wavelet transforms to detect the frequency of the heart sound signal

1) *Detection of center frequency:* It is well known that heart sound signals are not stationary signals [18]. Therefore the frequencies will vary with time. For proper analysis of heart sound signal we should know the frequencies at every instant and it is possible if we know the center frequency of the wavelet. With the help of the MATLAB we can easily find out this center frequency.

The following figures show how it is possible. In figure 12 two wavelets db2 and db6 have been selected. The center frequencies of them are shown in figure (13). In the same way we can select any wavelet and we also can find out their center frequencies. How does this help to know the frequency of the heart sound signal at every instant?

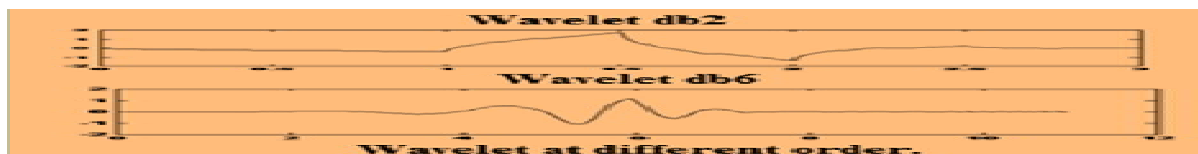


Fig.12. Example of Daubechies wavelet at order 2 and 6.

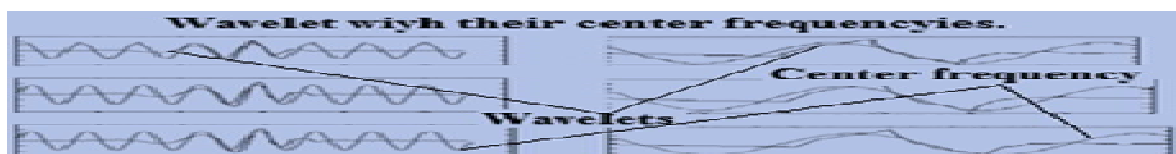


Fig.13. Center frequency of wavelets.

We know that in case of wavelet transform a section of the signal is selected first and then it is compared with a particular wavelet. The wavelet transform co-efficient shows the similarity between the section of the signal and the wavelet. Higher values of co-efficient indicate more similarity. More similarity means the frequency of the selected section of the signal is equal to the frequency of the wavelet. Ultimately we can find out the frequency of the heart sound signal at each section of the heart sound signal. If the center frequency of the wavelet does not match with the frequency of the mother signal, then what should be done?

International Journal of Innovative Research in Science, Engineering and Technology

(An ISO 3297: 2007 Certified Organization)

Vol. 5, Special Issue 13, October 2016

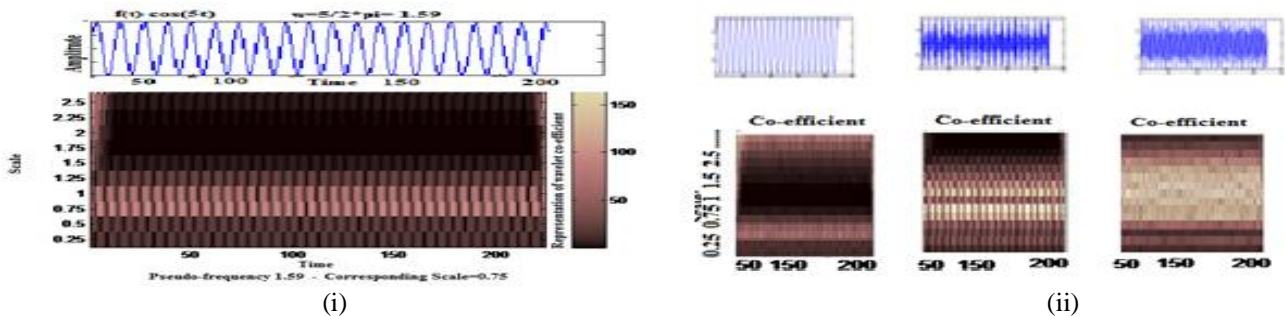


Fig.14.(i) Example of wavelet transform to a pure sinusoid with different scale .it shows different co-efficients at different level.(ii) It shows the wavelet co-efficient for three mother signal at different scales.

In figure (14) it is shown that the wavelet transform co-efficient are changing with different scale. Three mother signals have been selected and all the pseudo frequencies with the nearest mother frequency have been shown in the same figure . From the figure it is clear that the wavelet co-efficient are higher at the scale where the pseudo frequency is nearer to the mother frequency. Table 1 shows the true frequency and pseudo frequency.

TABLE II
TIME AND FREQUENCY RELATED RESULTS APPLYING WAVELET TRANSFORM

Subjects (Sample No)	CM-T (Sec)	CT-T (Sec)	S1-T (Sec)	S2-T (Sec)	HBR (Beat/Sec)	M-F (Hz)	S2-F (Hz)	S1-F (Hz)	
1	0.722892	0.714286	0.0132	0.0231	83	84	200.56	34.65	70.23
2	0.731707	0.731707	0.0143	0.0229	82	82	400.67	35.67	76.56
3	0.666667	0.681818	0.0133	0.0228	90	88	Nil	30.45	79.78
4	0.722892	0.731707	0.0129	0.0231	83	82	Nil	40.45	72.47
5	0.714286	0.722892	0.0140	0.0241	84	83	300.76	36.46	78.82
6	0.652174	0.659341	0.0126	0.0231	91	91	350.34	31.35	87.43
7	0.659341	0.666667	0.0150	0.0240	92	90	Nil	40.56	80.00
8	0.689655	0.689655	0.0142	0.0232	86	85	450.76	35.45	76.69
9	0.697674	0.705882	0.0151	0.0231	91	90	Nil	37.46	72.67
10	0.659341	0.666667	0.0146	0.0243	78	77	Nil	35.50	76.58
11	0.769231	0.779221	0.0139	0.0241	76	78	430.07	38.45	76.83
12	0.789474	0.769231	0.0137	0.0243	69	70	Nil	32.46	68.56
13	0.869565	0.857143	0.0146	0.0233	68	69	200.87	38.67	77.00
14	0.882353	0.869565	0.0142	0.0227	73	71	Nil	32.45	62.56
15	0.821918	0.84507	0.0148	0.0242	72	73	306.68	31.46	67.67
16	0.833333	0.821918	0.0138	0.0232	84	83	Nil	36.45	70.87
17			0.0151	0.0244	85	84	376.56	30.50	63.08
18									

**Notes:

- S1-T: Duration of 1st heart sound in second.
- S2-T: Duration of 2nd heart sound in second.
- CM1-T: Duration of a cardiac cycle measuring the duration of two consecutive M1 in second.
- CT1-T: Duration of a cardiac cycle measuring the duration of two consecutive T1 in second.
- S1-F: Frequency of 1st heart sound in Hz.

D. RESULT OF THE WAVELET TRANSFORM TO THE HEART SOUND SIGNAL

In the previous section we have applied the wavelet transform to detect and identify the position of a heart bit and the center frequency of the heart sound signal at different interval. In this section we have shown some results after applying different wavelet transform to the heart sound signal. Table 2 shows the results.

In figure(15) a complete heart sound signal has been shown. In chart 1 heart bit rate comparison has been shown. Some noise cancellation technique has been applied. From the figure (15) we see that for each and every heart bit we are getting higher wavelet co-efficient. The figure also shows the scale where the signal is more clear or noise free.

International Journal of Innovative Research in Science, Engineering and Technology

(An ISO 3297: 2007 Certified Organization)

Vol. 5, Special Issue 13, October 2016

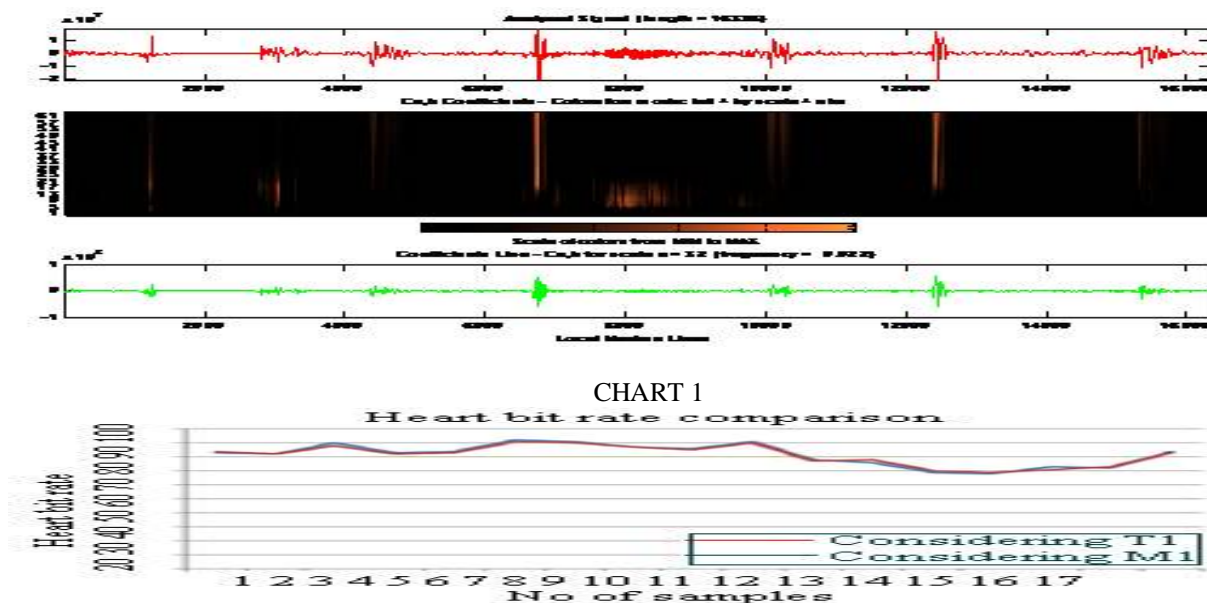


Fig.15. Complete noise free and pure cardiac sound signal. Two bits have been shown. The position of the heart bits have been shown by the wavelet co-efficient.

V. CONCLUSION

The aim of this work was to apply the wavelet transform and some innovative algorithms to the real time heart sound signal to monitor the cardiac disorder. To fulfill this we have made algorithm1 to detect the real time heart sound from the patients using DSP processor (TMS320C6713) which is working excellently. Algorithm1 serves brilliantly to apply the wavelet transform to the heart sound signal. Table1 shows the results related to the heart bit rate and frequency contains in the signal. Any disorder of the heart will give absurd result for the heart bit rate. What type of disorder that also can be found by analyzing the heart sound components like S1,S2 etc. it is known fact that heart bit rate differs from person to person that is also reflected in chart1.

REFERENCES

- [1] P.Várady "Wavelet-based adaptive denoising of phonocardiographic records" Proceedings – 23rd Annual Conference – IEEE/EMBS Oct.25-28, 2001, Istanbul, TURKEY. <http://www.dtic.mil/cgi-bin/GetTRDoc?AD=ADA410014>
- [2] Y. W. Bai, C. L. Lu, "The embedded digital stethoscopes use the adaptive noise cancellation filter and the type I Chebyshev IIR bandpass filter to reduce the noise of the heart sound", in *Proc. of 7th International Workshop on Enterprise networking and Computing in ealthcareIndustry, HEALTHCOM*, June 23-25, 2005. DOI: 10.1109/HEALTH.2005.1500459
- [3] A. S. Paul, E. A. Wan, A. T. Nelson, "Noise Reduction for Heart Sounds Using a Modified Minimum- Mean Squared Error Estimator with ECG Gating", in *Proc. Of 28th IEEE EMBS Annual International Conference*, New York City, USA, Aug 30-Sep 3, 2006, pp. 3385-3390, DOI: 10.1109/IEMBS.2006.259809
- [4] T.Usui, A.Matsubara, S.Tanaka "Unconstrained and Noninvasive Measurement of Heartbeat and Respiration Using an Acoustic Sensor Enclosed in an Air Pillow", SICE Annual Conference in Sapporo, August 4-6, 2004, Hokkaido Institute of Technology, Japan. SICE 2004 Annual Conference
- [5] A.Matsubara and S.Tanaka: "Unconstrained and noninvasive Measurement of Heartbeat and Respiration Using an Acoustic Sensor Enclosed in an Air Pillow", *SEE*, 40(6), printing determination (2004). SICE 2003 Annual Conference
- [6] DeGroff C G, Sanjay Bhatkar Hertzberg J, Shandas R, Valdes-Cruz L, Mahajan R L, "Artificial neural network- based method of screening heart murmurs in children", *American Heart Association* 103, 2711- 16, 2001. doi: 10.1161/01.CIR.103.22.2711
- [7] D. Kumar, P. Carvalho, M. Antunes†, J. Henriques, R. Schmidt‡, J. Habetha‡, "Near real time noise detection during heart sound acquisition", 15th European Signal Processing Conference (EUSIPCO 2007), Poznan, Poland, September 3-7, 2007, copyright by EURASIP <http://www.urasip.org/Proceedings/Eusipco/Eusipco2007/Papers/c21-e01.pdf>

International Journal of Innovative Research in Science, Engineering and Technology

(An ISO 3297: 2007 Certified Organization)

Vol. 5, Special Issue 13, October 2016

- [8] P. Carvalho, P. Gil, J. Henriques, M. Antunes Eugénio, "Low Complexity Algorithm for Heart Sound Segmentation using the Variance Fractal Dimension", in *Proc. of Int. Sym. on Intelligent Signal Processing*, Algarve, Portugal, Sep 3-7. 2005, pp. 937-942. DOI: 10.1109/WISP.2005.1531657
- [9] Raymond Watrous, "If the heart could speak *Picture of fall*", 2001 Siemens webzine. http://iopscience.iop.org/1742-6596/34/1/181/pdf/1742-6596_34_1_181.pdf
- [10] Lehner R J and Rangayyan R M, "A three channel microcomputer system for segmentation and characterization of the phonocardiogram", *IEEE Trans. on Biomedical Eng.* 34, 1987, 485-9. DOI: 10.1109/TBME.1987.326060
- [11]. Tavel ME., "Clinical phonocardiography and external pulse recording", 2d. Chicago: Year Book Medical Publishers, 1972; 38-41. <http://www.annals.org/content/78/6/992.2.extract>
- [12] Clinical Methods: The History, Physical, and Laboratory Examinations. 3rd Edition. Walker HK, Hall WD, Hurst JW, editors. Boston: Butterworths; 1990. <http://www.ncbi.nlm.nih.gov/pubmed/21250045>
- [13] Chissanuthat, Bunluechokchai and Weerasak Ussawongaraya, "A Wavelet-based Factor for Classification of Heart Sounds with Mitral Regurgitation", *International journal of applied biomedical engineering* vol.2, no.1 2009. <http://www.ijabme.org/File/vol2no1/J06.pdf>
- [14] H. Tang, T. Li, and T. Qiu, "Noise and disturbance reduction in cycle frequency domain based on non-linear time scaling," *IEEE . Biomed. Eng.*, vol. 57, no. 2, pp. 325-333, Feb. 2010. DOI: 10.1109/TBME.2009.2028693
- [15] J. Xu, L. Durand, and P. Pibarot, "Nonlinear transient chirp signal modelling of the aortic and pulmonary components of the second heart sound," *IEEE Trans. Biomed. Eng.*, vol. 47, no. 7, pp. 1328-1335, Jul. 2000. DOI: 10.1109/10.871405
- [16] J. Xu, L. Durand, and P. Pibarot, "Extraction of the aortic and pulmonary components of the second heart sound using a nonlinear transient chirp signal model," *IEEE Trans. Biomed. Eng.*, vol. 48, no. 3, pp. 277-283, Mar. 2001. DOI: 10.1109/10.914790
- [17] A. Baykal, Y. Z. Ider, and H. Koymen, "Distribution of aortic mechanical prosthetic valve closure sound model parameters on the surface of the chest," *IEEE Trans. Biomed. Eng.*, vol. 42, no. 4, pp. 358-370, Apr. 1995. DOI: 10.1109/10.376129
- [18] H. Koymen, B. K. Altay, and Y. Z. Ider, "A study of prosthetic heart valve sounds," *IEEE Trans. Biomed. Eng.*, vol. BME- 34, no. 11, pp. 853-863, Nov. 1987. DOI: 10.1109/TBME.1987.326006