Efficient Computation of Phonocardiographic Signal Analysis in Digital Signal Processor Based System

D. Balasubramaniam[1] and D. Nedumaran[2]

Abstract—**This article presents a real-time and cost effective system for the heart auscultation monitoring and hearing. The system design comprises of a Phonocardiographic pre-amplifier circuit with a TMS320C6711 Digital Signal Processor Starter kit (DSK) and its associated software. The Phonocardiogram signal from the pre-amplifier circuit is acquired through the CODEC input of the DSK and subjected to various signal processing techniques. Frequency analysis and component analysis are performed to identify the normal and pathological heart sound patterns using Short Time Fourier Transform (STFT), spectrogram display and Wavelet transform techniques respectively. To study the performance of the system, the analysis of heart sound patterns for various diseases were conducted. Finally the computational efficiency of the system was calculated by comparing the execution time of the algorithms in the proposed DSPPCG (Digital Signal Processor based Phonocardiogram) system with the PCPCG (PC based Phonocardiogram) system.**

Index Terms—**Heart auscultation, Digital signal processor, Phonocardiogram, Wavelet Transform**

I. Introduction

The auscultation of heart sound reveals valuable information about the functional integrity of the heart to the clinician. More information becomes available when clinician compares the temporal relationships between the heart sounds and the mechanical, electric events of the cardiac cycle [1-5]. Developing such kind of diagnostic skill through either a conventional acoustic stethoscope or an electronic one is itself a very special skill, and it may take years to acquire, in particular recognizing the actual heart sounds and the heart murmurs. Hence, recording of the heart sound in the form of the waveform display called Phonocardiogram (PCG) has been developed over the years to visually inspect the heart sound for diagnosis. Several research articles detailed about the computerized offline PCG analysis (time, frequency, and energy information of the acquired heart sound signals) and fetal heart sound analysis [6-10]. Such analysis is based on the dedicated hardware with specialized signal processing toolbox. In this study, a new method has been developed for the analysis of heart sound signals using digital signal processor based PCG (DSPPCG) system.

Heart sound signals are classified into S1, S2, S3, and S4 but among these four signals, the first two (S1, S2) are fundamental heart sounds, which are very common in both normal and abnormal heart functioning. Normal S1 sound represents the near-simultaneous closure of the mitral and tricuspid valves whereas abnormal S1 sound occur when there is a mitral valve disease (S1 may be loud with mitral stenosis and diminishing with mitral regurgitation). Normal S2 sound represent the near-simultaneous closure of the aortic and pulmonary valves, but splitting of S2 can occur in patients with atrial septal defect, pulmonic stenosis and right bundle branch block. Third heart sound (S3) will hear during the early diastole for normal children and young adults but may represent diastolic overload or dysfunction of the ventricle/heart valves in older adults. A fourth heart sound (S4, atrial sound), which occurs when increased atrial force or contraction is required to augment ventricular filling, is generally considered as an abnormal finding. Ventricular hypertrophy, pulmonary arterial hypertension and pulmonary stenosis are some of the clinical abnormalities that can cause an S4 sound. A heart murmur may be pathologic or innocent and can sometimes lead to the detection of underlying structural heart disease. Most often, heart murmurs represent turbulent blood flow within the heart and are heard as vibrations on auscultation. Most of these conditions of the heart are attempted to diagnose correctly by analyzing the heart sound signal in the proposed DSPPCG system. Two methods are conducted in the DSPPCG system and are given below.

1. Identification of PCG components from STFT spectrum and the spectrogram display
2. Identification of PCG components using Wavelet denoising method

Finally the performance of the DSPPCG system in executing the developed algorithms for the analysis of the PCG signals is estimated by a comparative study of the algorithms in the PCPCG system.

II. Experimental Setup

Initially the Phonocardiograph (PCG) circuit was designed and developed as a prototype model in our laboratory. The circuit comprises of an electrets microphone, TL084 Quad operational amplifier and the Sellen-Key Low pass filter. In this circuit, the Microphone (Air coupled sensor) acts as a sensing element that measures pressure waves induced by chest-wall movements and the heart pump. The audio signal is pre-amplified and low pass filtered by the TL084 based preamplifier and low pass filter circuits respectively. The signal is further amplified by another amplifier (constructed using the sparing op-amp of TL084),

D. Balasubramaniam1 and D. Nedumaran2,1,2Central Instrumentation and Service Laboratory, University of Madras, Guindy Campus, Chennai – 600025, India, 1IEEE Student Member (email: signalist@gmail.com).

which enhances the amplitude of the signal to the required level (1V to 3V range) for data acquisition through the CODEC input of the TMS320C6711 DSP Starter Kit (DSK). The CODEC of the DSK supports upto a maximum of 8 kHz sampling rate, which is more than sufficient for digitizing all the components of the PCG signal.

The DSK interfaced with the Desktop PC through the IEEE1284 Peripheral Parallel port interface acquires the PCG signal for further signal processing and analysis operations. The signal processing and analysis operations are developed in the form of application programme using the Code Composer Studio (CCS) [11, 12], an integrated development environment provided by the Texas Instruments Inc. The processed PCG signal can be heard through the earphone connected with the audio codec output of the DSK. In addition to this, the processed PCG signal can be visualized in the display.

Figure 1. Photograph of the TMS320C6711 DSK Based Phonocardiogram System

In the PCPCG system, the PCG signals from the PCG preamplifier board is directly coupled with the audio input of the PC and acquired through the data acquisition modules. The signal processing operations are performed through the application program developed in the Matlab environment. The photograph of the developed DSPPCG system with the acquired PCG waveform is shown in the Fig.1.

III. METHODS

The PCG signal is digitized through the in-built audio codec of the DSK, at the sampling frequency of 4.5 kHz, since most of the normal and abnormal heart (murmur) sounds lies well within the frequency range of 30 Hz to 2 kHz. Also, the frequency of the fundamental heart sounds namely S1 and S2 are in the range of 30 Hz - 300 Hz. The normal PCG signal for a healthy individual acquired through the PCPCG system and the DSPPCG system are shown in Fig. 2 & Fig.3 respectively.

To analyze the frequency components of the PCG signal, a 1024 Short Time Fourier Transform (STFT) algorithm was implemented in both the systems. Fig. 4 & Fig. 5 shows the magnitude spectrum of the normal heart sound processed in both the systems.

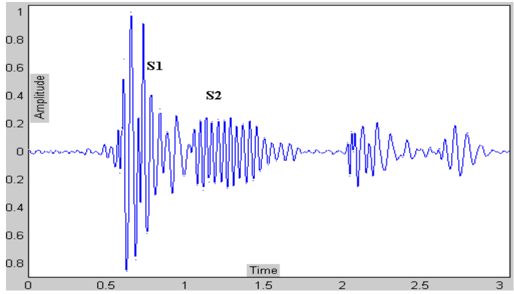

Figure 2. Normal PCG signal acquired in the PCPCG System

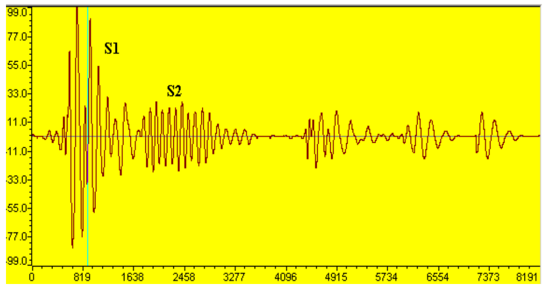

Figure 3. Normal PCG signal acquired in the DSPPCG system

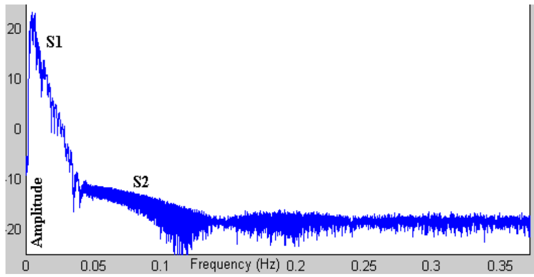

Figure 4. Spectrum of the Normal PCG signal in the PCPCG system

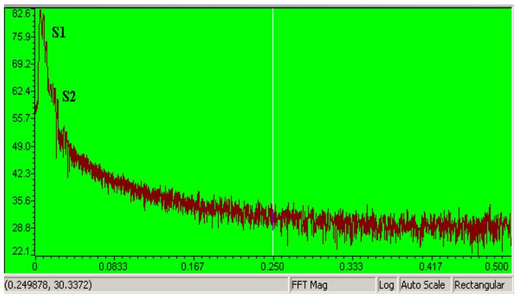

Figure 5. Spectrum of the Normal PCG signal in the DSPPCG system

Fig. 6 & Fig. 7 shows the representation of the abnormal (Mitral Valve Prolapse (MVP) subject) heart sound signal in the frequency range from 0 Hz to 2000 Hz. MVP is due to the improper closure/opening of the mitral valve, which causes the blood flow in the reverse direction.

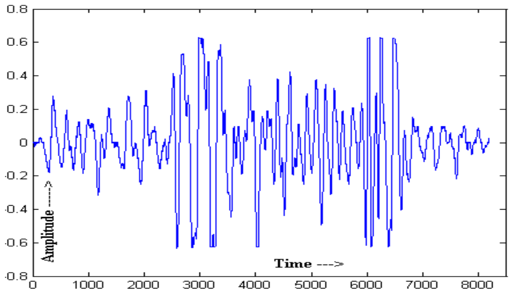

Figure 6. Abnormal (MVP) PCG acquired in the PCPCG system

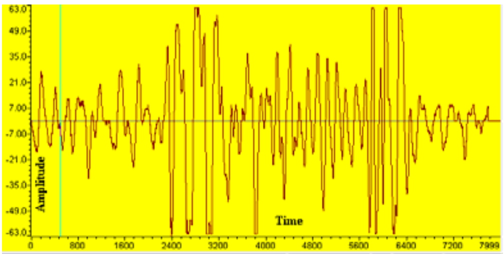

Figure 7. Abnormal (MVP) PCG signal acquired in the DSPPCG system

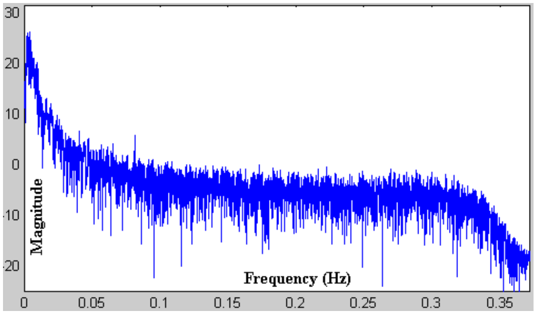

Figure 8. Spectral response of the Mitral Valve Prolapsed case in the PCPCG system

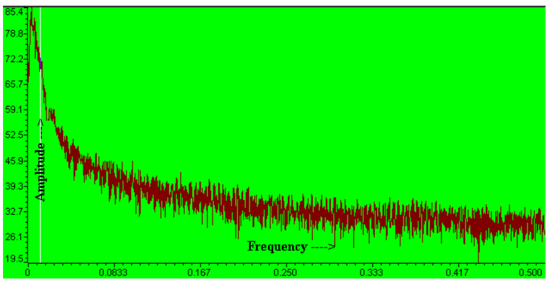

Figure 9. Spectral response of the Mitral Valve Prolapsed case in DSPPCG system

Fig. 8 and Fig. 9 shows STFT spectrum of the abnormal (MVP) heart sound signal in the PC & DSP systems respectively. The output display shows the logarithmic scale of the STFT magnitude using 1024 FFT over the sampling frequency of 11025 Hz. Also the output consists of only (memory limit) 32768 data size in the PCPCG system, where as for the DSPPCG system, the FFT magnitude was obtained up to 64000 data. For the abnormal condition, the spectrum includes S1, S2, S3, S4 (Pulmonary arterial Hypertension) and murmurs, hence more number of samples are required for analysis. The spectrum includes the original heart sound, murmurs and the unwanted signals. From the spectrum it is very difficult to identify the fundamental frequency components pertaining to S1 and S2 signals using STFT technique. For the detailed extraction of the received signals both the normal and abnormal (Fig. 2 & Fig. 6), the spectrogram display using the STFT have been formed. The results are shown in the Fig. 10 & Fig. 11.

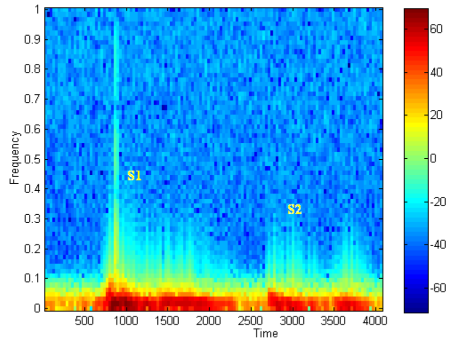

Figure 10 Direct Spectrogram of the normal Heart Sound in the PCPCG system

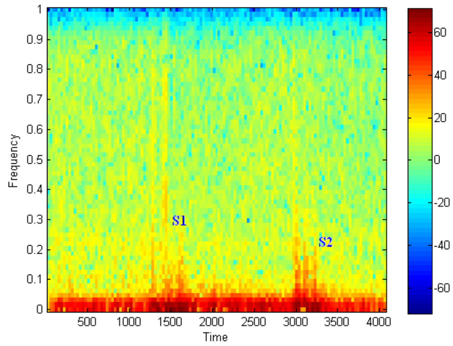

Figure 11 Direct Spectrogram of the Abnormal Heart sound (MVP) case in PCPCG system

The received signal is divided into eight segments with 50% overlap; each segment is windowed with a Hamming window. The number of frequency points used to calculate the discrete Fourier transforms is equal to the maximum of 128.

To extract the abnormal heart signal, wavelet transform using Morlet basis function has been employed in this study. The Morlet wavelet basis function is chosen for this study due to its matching property with the PCG signal components [13, 14] and the exact occurrence of the PCG component during the time-frequency analysis. Fig. 12 shows the Morlet psi function [15] and it is explained mathematically in equation 1.

$$\psi(t) = \pi^{-1/4}\left(e^{i2\pi f_0 t} - e^{-(2\pi f_0)^2/2}\right)e^{-r^2/2} \quad \cdots 1$$

Where $\pi^{-1/4}$ is the scaling function and it is used for the normalization in view of reconstruction, f_0 is the center frequency of the Mother wavelet.

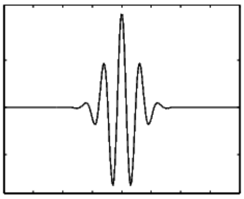

Figure 12. Morlet psi function

The second term in the brackets is known as the correction term which corrects for the non-zero mean of the complex sinusoid of the first term. The wavelet exhibits symmetry property and hence all functions decay quickly to zero. This Morlet wave function is employed and algorithm is developed for denoising the fundamental heart sound in both the DSPPCG and PCPCG systems. The algorithm is tested for different heart diseases in order to estimate its efficiency in identifying the diseased conditions.

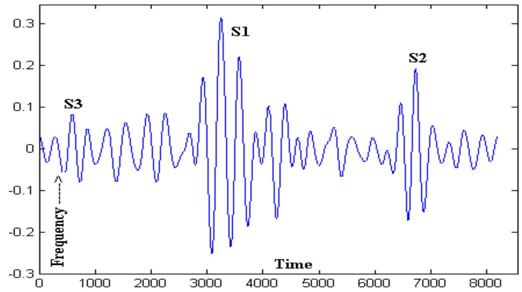

Figure 13. Extraction of Fundamental Components of an Abnormal (MVP) Heart sound using Morlet wavelet in the PCPCG system

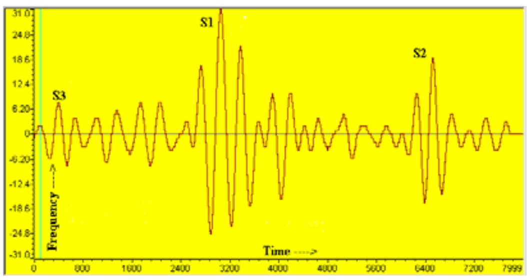

Figure 14. Extraction of Fundamental Components of an Abnormal (MVP) Heart sound using Morlet wavelet in the DSPPCG system

We have conducted studies for more than 45 abnormal subjects and the results obtained in all these cases clearly separate the individual components of the PCG, which can be used as a preliminary tool for clinical diagnosis. Fig. 13 & Fig. 14 show the denoised version of the Systolic Mitral Valve Prolapsed valvular heart signal in both the systems. Thus, the denoised PCG waveform display using Morlet wavelet provides the fundamental frequency components of the PCG for diagnosis.

IV. Computer and DSP Analysis Software Pipelining For The Code Optimization

The main aim of this study is to find the structural programming concepts of the DSP for improving the computation efficiency of DSPPCG system over the PCPCG system with the intention to include the DSPPCG system for routine clinical use. In the PCPCG system, the computation of FFT algorithm is based on the Cooley-Tukey decomposition, where as in the DSPPCG system optimized FFT algorithm is used to perform the operation. Optimization involves the software pipelining (*Prolog*, *loop Kernel, and Epilog*). In this method all the functional units (inside the processor) are used absolutely in parallel mode. All the instructions executed in parallel are in the loop. The entire loop kernel is executed in one cycle. In the final stage of the execution (Epilog) necessary instructions in the loop kernel must complete all iterations.

Table 1 shows the comparison of calculation efficiency of STFT and Wavelet techniques implemented to extract the PCG components in the PCPCG system (Intel Pentium 4 clock frequency is 1.70 GHz) and the DSPPCG system (TMS320C6711, clock frequency is 150 MHz). In both the system, a 1024-FFT algorithm has been implemented for calculating the STFT spectrum with a sample size of 32768 samples. The internal clock of the both the systems are used to calculate the time required to execute the overall algorithm for the STFT and Wavelet Transform.

TABLE I. Calculation Efficiency of DSPPCG System and PCPCG System

Patients ID	**Component Extraction**	
	Pentium 4 (m sec)	DSP (C6711) (µs)
SMP	781	664.751
MS	881	678.331
PS	840	657.832
TR	821	682.215

From the table 1, it is clear that the execution speed of the entire algorithm in the DSPPCG system is approximately 1000 times faster than the PCPCG system due to the DSP structured coding techniques. Thus, the DSP based algorithms can be implemented in the real-time medical system designs for routine clinical use.

V. Conclusion

In this work, a PCG pre-amplifier circuit is designed and interfaced with the DSPPCG as well as PCPCG systems to evaluate the performance of the system in executing the signal processing algorithms for real-time applications. The

STFT analysis is used to estimate the spectral components of the PCG signal and Wavelet transform is implemented for the extraction of PCG components. In both these studies computational efficiency of the algorithm in terms of execution speed of the algorithm are calculated for both the DSPPCG and PCPCG systems. The results of this study reveal that the DSPPCG system is suitable for routine clinical diagnostics due to its real-time analysis of the PCG signal. Also, the DSPPCG system has fast execution time, structural programming facility and flexibility of tuning the algorithm for future developments.

Traditionally heart auscultation is an initial and fundamental procedure to inspect a patient. Applying these diagnostic procedures in routine clinical practices would results in efficient and accurate diagnosis of the disease at an early stage. The proposed DSPPCG system would be a nice attempt to reveal the power of DSP in designing the medical system, which will make the PCG as a tool for the doctors and the physicians to diagnose a patient preliminarily. The future scope includes the implementation of the spectrogram calculation in the DSPPCG system.

ACKNOWLEDGMENT

The authors are gratefully acknowledged the financial assistance provided by the Indian Council of Medical Research (ICMR) to execute this work.

REFERENCES

[1] John G. Webster, Medical Instrumentation - Application and Design, 3rd ed. 1998, John Wiley & Sons, Inc.

[2] Rangayyan M. and Lehner R.J., 1988, Phonocardiogram signal analysis: a review. CRC Critical Reviews in Biomedical Engineering, 15, 211–236.

[3] Bernard Karnath, William Thornton, Auscultation of the Heart, Review of clinical signs, pp. 39-43, September 2002.

[4] Paul Erne, Beyond auscultation – acoustic cardiography in the diagnosis and assessment of cardiac disease, Review article, SWISS MED WKLY 20 08;138(31–32):439–452.

[5] Jalel Chebil and Jamal Al-Nabulsi, Classification of Heart sound signals using Discrete Wavelet Analysis, International Journal of Soft Computing 2(1); 37-41, 2007.

[6] Faizan Javed, P A Venkatachalam and Ahmad Fadzil M H, A Signal Processing Module for the Analysis of Heart Sounds and Heart Murmurs, Journal of Physics: Conference Series 34 (2006) 1098–1105.

[7] Debbal S.M. Amin and Bereksi-Reguig Fethi, Features for Heartbeat Sound Signal Normal and Pathological, Recent Patents on Computer Science, 2008, 1, 1-8.

[8] Vladimir Kudriavtsev, Vladimir Polyshchuk and Douglas L Roy, Heart energy signature spectrogram for cardiovascular diagnosis, *BioMedical Engineering OnLine* 2007, 6:16.

[9] E. Kail, S. Kho´or, B. Kail, K. F¨ugedi, F. Bal´azs, Internet Digital Phonocardiography in Clinical Settings and in Population Screening, Computers in Cardiology 2004;31:501−504.

[10] Xuan Zhang, Louis-Gilles Durand, Lotfi Senhadji, Howard C. Lee, and Jean-Louis Coatrieux, Time-Frequency Scaling Transformation of the Phonocardiogram Based of the Matching Pursuit Method, IEEE TRANSACTIONS ON BIOMEDICAL ENGINEERING, Vol. 45, No. 8, August 1998.

[11] Document tms320c6711d.pdf & sprz173p.pdf, TMS320C6711D Floating-Point Digital Signal Processor (Rev. B), June 2006, www.ti.com.

[12] Document SPRC121, TMS320C67X DSP Library, www.ti.com.

[13] Document SPRC060, TMS320C67X Fast RTS system library, www.ti.com.

[14] S. Rajan, E. Budd, M. Stevenson, R. Doraiswami, Unsupervised and Uncued Segmentation of the Fundamental Heart Sounds in Phonocardiogram Using a Time-Scale Representation Proceedings of the 28th IEEE EMBS Annual International Conference New York City, USA, Aug 30-Sept 3, 2006.

[15] Slobounov, S., Tutwiler, R. L., Slobounova, E., & Fedon S, The Perception of Postural Instability as Revealed by Morlet Wavelet Transform in EEG, 0-7803- 5073-1/98/$ 10.00 ©1998 IEEE.