How to Cite:
Vakamullu, V., & Mishra, M. (2022). Variational mode decomposition based automated fetal PCG denoising and extraction. *International Journal of Health Sciences*, *6*(S3), 6567–6579. https://doi.org/10.53730/ijhs.v6nS3.7469

Variational mode decomposition based automated fetal PCG denoising and extraction

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***Abstract*---**Congenital cardiac anomalies of fetus are often characterized by the unprecedented changes in the auditory properties of cardiac sounds occurs during the gestation period of pregnant women. These abnormalities are often seen in inconsistent patterns of heart sounds that are driven by asynchronous variations in heart rates of mother and fetus. This hostile situation becomes severe if it is untreated and might threaten to life risk in pregnant women. In this work, we proposed a novel and automated signal processing paradigm using Variational Mode Decomposition (VMD) to detect and extract the mother and fetus heart sounds from the raw PCG signals recorded from outer surface of the maternal abdomen. The proposed framework constitutes a couple of cascaded VMD blocks: The first VMD block alleviates the raspatory noises and other artifacts from the raw PCG signal; while the Next one, decomposes the mother and fetus heart sounds obtained from its preceding block. A publicly available Shiraz University Fetal Heart Sounds Database is used to test the efficacy of the proposed model. In addition, noisy PCG corpus characterized by the additive white gaussian noise is used to test the efficacy of the proposed network. Finally, the obtained results are found promising and outperforms the state of art techniques for both the raw PCG and noise corrupted raw PCG recordings. Since the proposed method is non-invasive type and uses simple electronic stethoscope to record the PCG signals, it doesn't produce the electromagnetic radiation and any adverse health impairments. The detailed refinement of this technique can be used as computer assisted heart sound analysis tool for pregnant women in hospitals, clinics and health care centres.

International Journal of Health Sciences ISSN 2550-6978 E-ISSN 2550-696X © 2022.
Manuscript submitted: 27 March 2022, Manuscript revised: 18 April 2022, Accepted for publication: 9 May 2022

***Keywords*---**fetal phonocardiogram, variational mode decomposition, maternal PCG.

Introduction

The gestation is extremely important period for every pregnant woman, during which the maternal health and fetus growth is simultaneously to be taken care. Particularly, timely monitoring of the heart sounds, heart rate variability and cardiac functionality of mother and fetus is essential task during this period. Fetal heart rate (FHR) monitoring and assessment begins from 24th week of gestation and follows the regular check-up daily or once in week to track status of fetus health. The most common tool used for this task is Doppler Ultrasonographic Cardiotocography (CTG) [1]. Though the CTG is popular and effect non-invasive technique, it asserts certain adverse effects on fetus health due to high energy ultrasonic radiation emitted by CTG. In addition, CTG often fails to distinguish the maternal and fetal rhythms [2], [3]. Fetal phonocardiography (FPCG) is another alternative approach to record the persistent heart sounds from the maternal abdomen [4]. The maternal heart sounds predominantly consist of 4 components viz. S_1, S_2, S_3, S_4. These sounds are generated due to the vibrations caused by seamless blood flow between the various heart chambers thorough heart valves. However, these heart sounds are precisely heard by using a widely accepted equipment called stethoscope. Though the stethoscope is reliable device for detecting cardiac sounds, it doesn't impart the facility of visualizing the heart sounds and their latent components of various components of heart sounds. Hence, this hostile situation leads to implementation of electronic stethoscope, which helps to record and display the PCG waveforms along with the hearing facility [5]. On the other hand, the PCG signals captured from the maternal abdominal are fully corrupted by the noise, which makes the signals unreliable for health assessment of mother and fetus. Various noise sources that contaminate the maternal PCG includes fetal movement generated acoustic noise, noise generated due contraction and expansion of uterus muscles, maternal digestive tract vibrations, motion artifacts of mother, measurement errors caused due to movement of sensors, and Environmental noises [6-8].

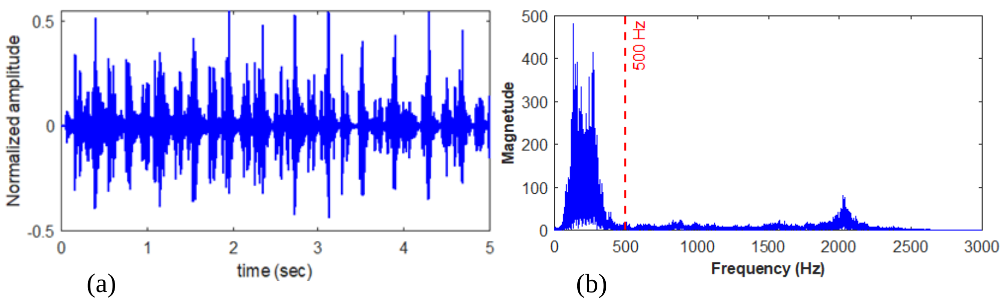


Fig 1. (a) Raw PCG signal captured from mother's abdomen using Littman electronic stethoscope. (b) Frequency spectrum. Curtsey: https://physionet.org/content/sufhsdb/1.0.1/

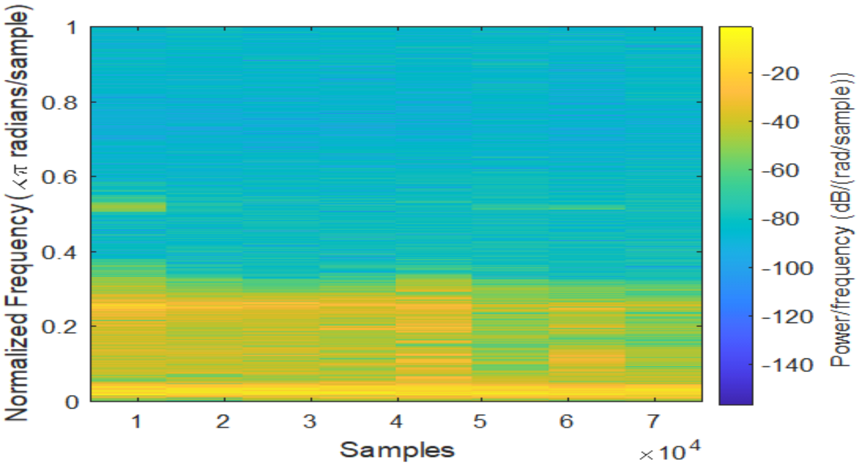


Fig 2. Power spectrum of the Raw PCG signal contaminated by noise, abdominal sound and respiratory sounds. Curtsey: https://physionet.org/content/sufhsdb/1.0.1/

Fig 1. Depicts the noisy PCG signal and it's frequency spectrum, While Fig 2. depicts the power spectrum of the maternal abdomen fPCG recordings. Fetal PCG amalgamated with these noises cannot accurately confer the latent details of the heart sound components of mother and fetus which turn makes the assessment of heart functionality is a tedious task. Therefore, there is need of robust and accurate signal processing techniques which can alleviate the noises, decomposes the various sound components, opt-out the artifacts, represent the spectral components and separate the maternal and fetal PCG waves and hence the resultant waveforms become the ease of further analysis and cardiac abnormality detection. The rest of the article is structured as follows: section II discussed the state of art and literature of fPCG extraction. Section III describes the mathematical background and methodology of the proposed frame work. Section IV illustrates the experimental setup; section V delineates about the results and discussion and section VI presents the concluding remarks of the present work.

Related work

In classical fetal phonocardiogram, numerus non-invasive methods are existing based on cardiac signals [9] such as the electrocardiogram (ECG) for recognizing electrical activity of the heart or the phonocardiogram (PCG) for mechanical vibrations of heart. The sensing elements are usually positioned on the outer surface of the mother womb and the captured signals are fed to subsequent signal processing units to perform various mathematical and numerical operations on the raw PCG. Conventionally ECG is used to estimate the heart rates by classical methods for infants or adults by detecting *R* peaks in ECG signals [10]. But ECG taken over abdomen, imparts very low power fetal signals compared to that of maternal recordings, which in turn makes the *R* peaks detection is a difficult task. More often, this difficulty can be overcome by the aid of independent component analysis applied on the source signal to separate it's latent components [11]. However, this method requires bunch of sensors to be positioned on the mother thorax and outer surface of the abdomen, and hence not suitable for a real time clinical setup and execution. Hence, it is advisable to captures the audio properties of the heart instead of its electric activity. The sound waveforms acquired from mother's abdomen using electronic stethoscope yields the qualitative information of the heart functionality, However, these waveforms are often contaminated by noise and other innate signals. Hence, distinguished signal processing techniques have been adopted over the years to eliminate the noises and makes ease of processing [12]

Numerous signal processing techniques pertaining to fetal PCG analysis and decomposition are presented in literature However, the majority of conventional filtering-based methods are not effective due their inability in fine tuning of the filter parameters and linear characteristics of filter coefficients. The linear filters miserably fail to analyse the nonlinear of fetal phonocardiogram signals [13]. Further, Adaptive filtering technique based fPCG analysis is also presented in [14], though it performs bit better than static filters, they suffer from lack of robustness. On the other hand, various methods representing the frequency and power spectrums based on time-frequency resolution like short-time Fourier transform (STFT) [15], wavelets transform [16] are probed for fPCG analysis. However, they are also end up with the limitations of linearity and no proper thumb rule for kernel designs for blind source separation (BSS) [17]. The most familiar PCG-based techniques are presented in [18], [19]. However, these methods depend on the locations and time stamps the internal components of PCG signal and finds difficulty in tracing the envelops. The envelops and locations pertaining to S1 and S2 sounds are observed as most audible cardiac sounds and correspond to the closure of respectively the atrial-ventricular, and the aortic and pulmonary valves. Fig.1 displays the fetal PCG and corresponding envelops, locating and detecting S1 and S2 occurrences is a pathetic task in fetal PCG, particularly fPCG corpus is heavily contaminated by noises (such as gastric or liquid). Further, many other fPCG signal processing techniques are explored in literature to deal with noisy fPCG and components decomposition based on: least mean square (LMS) linear prediction [20], Wavelet Transform [21], adaptive Wiener filtering [22], spectral subtraction [23], conventional filtering [24], blind source separation [25] auto or cross correlation [26], Wigner Ville Distribution - WVD [27], Short Time Fourier Transform - STFT [28], Hilbert Transform [29]. In recent times, fPCG Processing Using Empirical Mode Decomposition (EMD) and Singular Value Decomposition (SVD) is proposed in [30]. Matching Pursuit (MP) method for fPCG in telemedicine system [31] Fractal Dimension (FD) analysis in association with Wavelet transform [32] is presented.

In the light of the above investigation, it clearly understood that the existing methods fail in one way or the other to manifest the accuracy in fPCG extraction, identification of locations of heart sound components, noise alleviation and decomposing. Hence, there is need of a novel technique to use as a reliable and sophisticated tool to full fill the requirement of fPCG analysis. Variational mode decomposition (VMD) [33, 34] is recently introduced signal processing technique for non-linear and non-stationary signal analysis. This technique is implemented based on LaGrange multiplication and Alternating Direction M*ethod* of Multipliers (*ADMM*). Section III briefly explains the underlying mathematical intuition and algorithms pertaining to VMD.

Methodology

Variational Mode Decomposition

Variational mode decomposition is a signal decomposition algorithm predominantly applies on the non-linear and non-stationary signals to decompose into group of individual narrowband sub components called Modes. The primary objective of the VMD algorithm is to decompose any non-linear and non-stationary multi frequency toned signal f into a finite number of narrowband sub-signals (modes), u_k, each mode k is distributed around a centre frequency ω_k, which is to be computed along with the decomposition. The resulting constrained variational problem is the following:

$$\min_{\{u_k\},\{\omega_k\}} \left\{ \sum_k \left\| \partial_t \left[\left(\delta(t) + \frac{j}{\pi t} \right) * u_k(t) \right] e^{-j\omega_k t} \right\|_2^2 \right\} \quad \text{s.t.} \quad \sum_k u_k = f \qquad \text{-----------------------} (1)$$

where $\{u_k\}=\{u_1,\ldots,u_K\}$ and $\{\omega_k\}=\{\omega_1,\ldots,\omega_K\}$ are shorthand notations for the set of all modes and their centre frequencies, respectively. Equally, $\Sigma_k = \sum_{k=1}^{K}$ is understood as the summation over all modes. The individual narrow band sub signal components/modes can be derived as

$$u_k^{n+1} = \arg\min_{u_k, u_k \in X} \left\{ \int_0^{\infty} 4\alpha(\omega - \omega_k)^2 |u_k(\omega)|^2 + 2 \left| f(\omega) - \sum_i u_i(\omega) + \frac{\lambda(\omega)}{2} \right|^2 d\omega \right\} \qquad \text{-----------------------} (2)$$

The centre frequencies ω_k do not appear in the reconstruction fidelity term, but only in the bandwidth prior. The relevant problem thus reads:

$$\omega_k^{n+1} = \arg\min_{\omega_k} \left\{ \left\| \partial_t \left[\left(\delta(t) + \frac{j}{\pi t} \right) * u_k(t) \right] e^{-j\omega_k t} \right\|_2^2 \right\} \qquad \text{---------------------} (3)$$

Hence VMD algorithm described in this section is directly applied to fatal PCG signal obtained from the mother's abdomen to alleviate the various noise sources and separates the mother and fetus PCG waveforms from combined PCG. Section IV describes the data acquisition and experimental setup of the proposed framework.

Experimental setup
Data acquisition

Data acquisition is one of the key steps of fPCG processing. In this work, we have used the fPCG corpus obtained from the two publicly available online sources viz. www.physionet.com and Shiraz University Fetal Heart Sounds Database. The Physionet database constitutes 26 PCG signals collected from maternal abdomen during the gestation week between 31 and 40. All the data is pertaining to healthy women of different ages in between 25 to 35 years old. All the recordings were captured by an experienced cardiac specialist in a private clinical by the aid of a portable phonocardiograph device (Fetaphon Monitoring System by Pentavox). Each PCG wave lasts around 20 *sec* duration with the sampling rate of 44,100 Hz. On the other hand, The Shiraz University Fetal Heart Sounds Database used in this work constitutes recordings obtained from 109 pregnant women carrying single and twin pregnancies. All the recordings are captured by the specialized doctors at Hafez Hospital of Shiraz University of Medical Sciences, Shiraz, Iran, form the lower abdomen of the pregnant women aged between 16 and 47 years old with highly precise digital stethoscope. In total, 99 subjects are signal recorded, three subjects are recorded twice and seven are twin subjects, to result in 119 recordings. Each PCG wave form is elapsed for average duration is about 90 seconds. The data was recorded with wide-band digital stethoscope at 44,100 Hz sampling rate. Further, each PCG signal obtained from the database is sliced to the the duration of 5 sec. Eventually, all the sliced signals are inputted to the frame work shown in Fig 3. for further processing.

Experimentation

The flow diagram representing the fetal PCG extraction and denoising is depicted in Fig. 3.

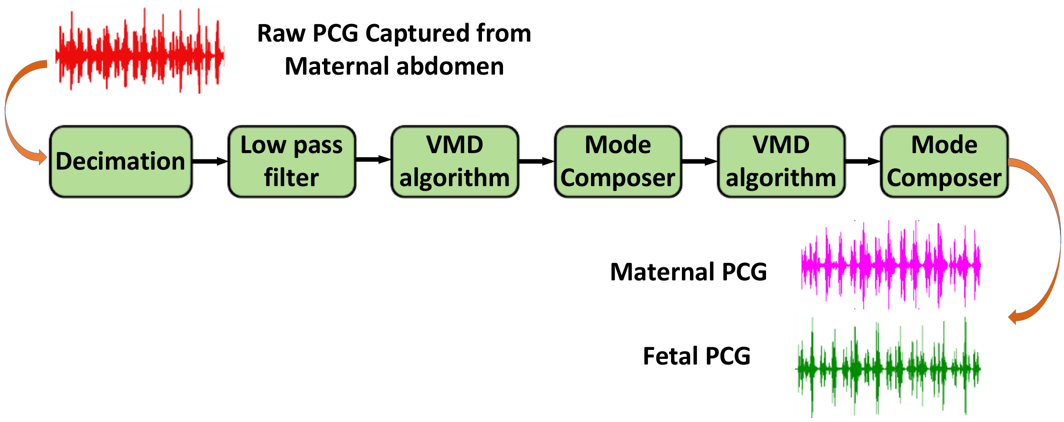


Fig. 3. Flow diagram representation of proposed framework for fetal PCG denoising and extraction

The fPCG analysis depicted in Fig.3 undergoes the series of blocks, in which each and every block employs specific operation on the raw PCG signal and eventually delivers the fetal and maternal PCG waveforms as separate entities. The raw PCG signals recorded using electronic stethoscope from maternal abdomen possess the sampling frequency of 44,100 Hz. Hence, at first, the raw PCG are fed to decimator, in which the PCG corpus is down sampled to 16 kHz. Next, the output of the decimator is fed to lowpass filter of 2 kHz corner frequency to remove the high frequency noise components associated with raw PCG. Next, the filtered output is fed to 1st VMD algorithm to decompose and produce low and high frequency sub signals. Next, the resultant sub signals are fed to mode composer, where the noise sources are removed and remaining modes are summed up to form a noise free fPCG signal. Next, the denoised fPCG signal is fed to 2nd VMD algorithm and again decomposed into low and high frequency sub signals. Next, the decomposed sub signals are sent to mode selection and mode combining block. At last, mode composer block selects the appropriate modes and combine them to produce un overlapped maternal and fetal PCG signals. Therefore, the entire process ends up with the generation of pure PCG signals of fetus and mother. This way, the proposed framework denoises the raw fPCG and extracts the individual components of maternal and fetal PCG from the combined PCG corpus.

Results and Discussion

In this work, the fetal PCG denoising and extraction is performed using the cascaded structure of VMD algorithms shown in Fig 3. Two most reliable and publicly available fPCG databases viz. Shiraz University Fetal Heart Sounds Database and Physionet database are used to assess the performance of the proposed framework. Each PCG signal grabbed from the database is sliced to 5 sec durations and fed to the proposed framework. Further, each signal undergoes the series of operations illustrated in Fig 3. The 1st VMD Algorithm decomposes the filtered PCG signal into group of modes as shown in Fig 4. while Fig 5. illustrates the frequency spectrum of each individual mode generated from the 1st VMD algorithm. From Fig 5. it is clearly observed that modes numbered from 1 to 6 constitutes high frequency noise components, while modes numbered from 7 to 9 constitutes the maternal and fetal heart. sounds. From the figure it is further observed that modes 1 to 6 lie above the 500 Hz, and modes 7,8,9 lie below the 500 Hz. Since 500 Hz is the demarcation frequency line in between the

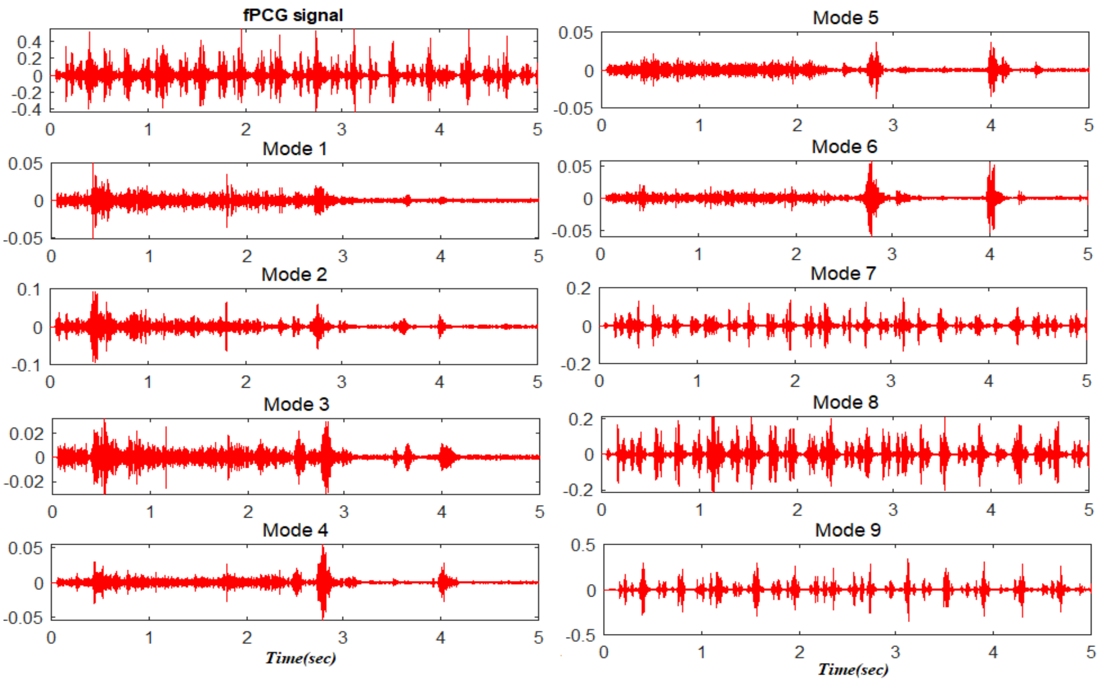


Fig 4. fPCG signal and it's decomposed modes using 1st VMD algorithm

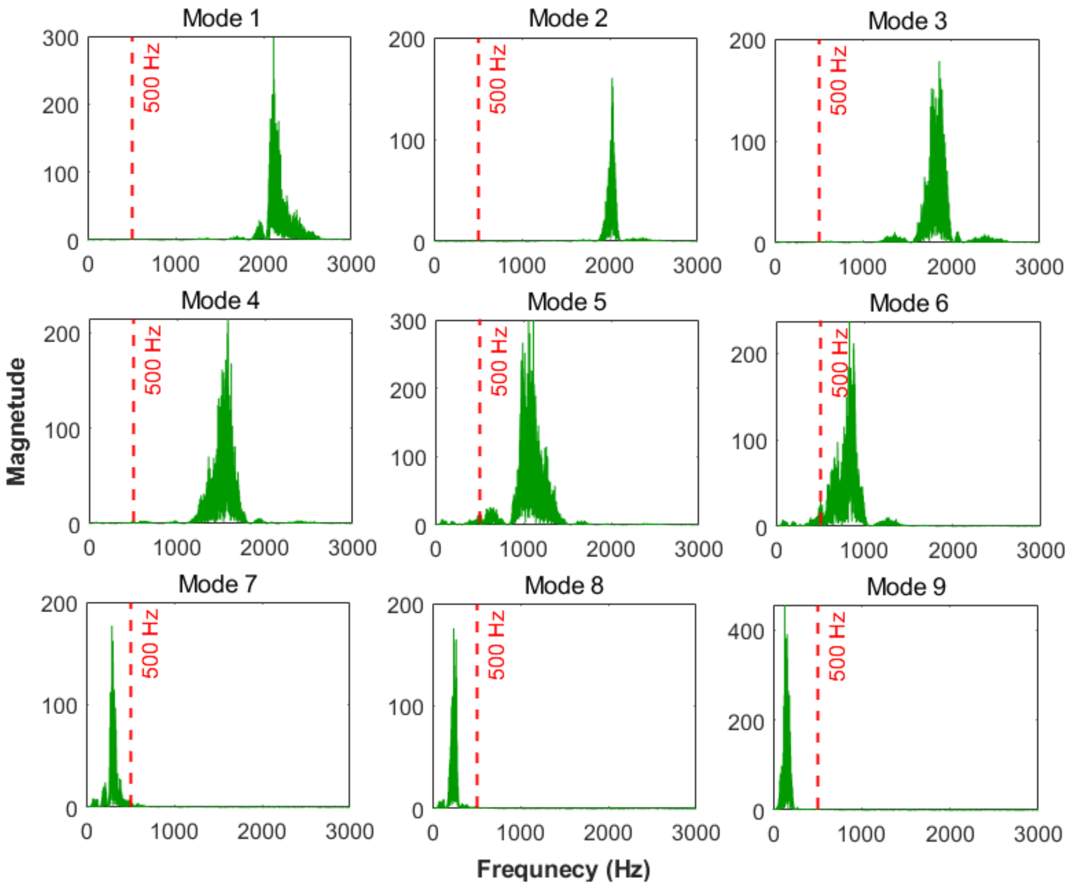
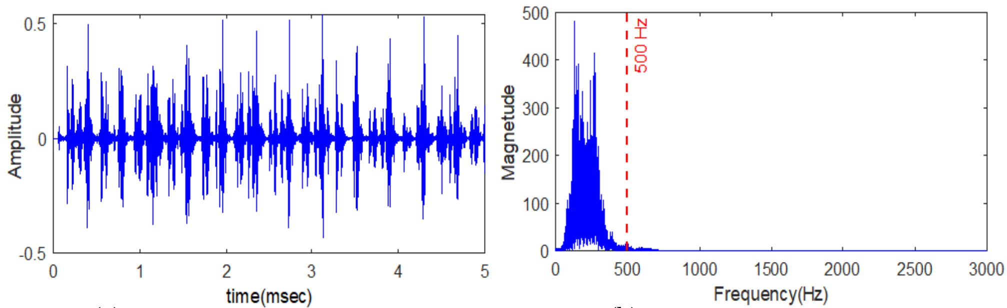


Fig 5. Frequency spectrum of each individual mode generated by 1st VMD algorithm



(a) (b)

Fig 6. (a) Denoised PCG signal obtained by combining mode 6 mode 7 and mode 8. (b) frequency spectrum of denoised PCG noise and original heart sounds, mode 7, mode 8 and mode 9 are selected and combined to produce the denoised fPCG. Fig 6 depicts the denoised fPCG and it's frequency spectrum obtained from mode combining block. and Fig 7 depicts the decomposed modes and Fig 8. Depicts the frequency spectrum of each individual modes obtained from 2nd VMD algorithm.

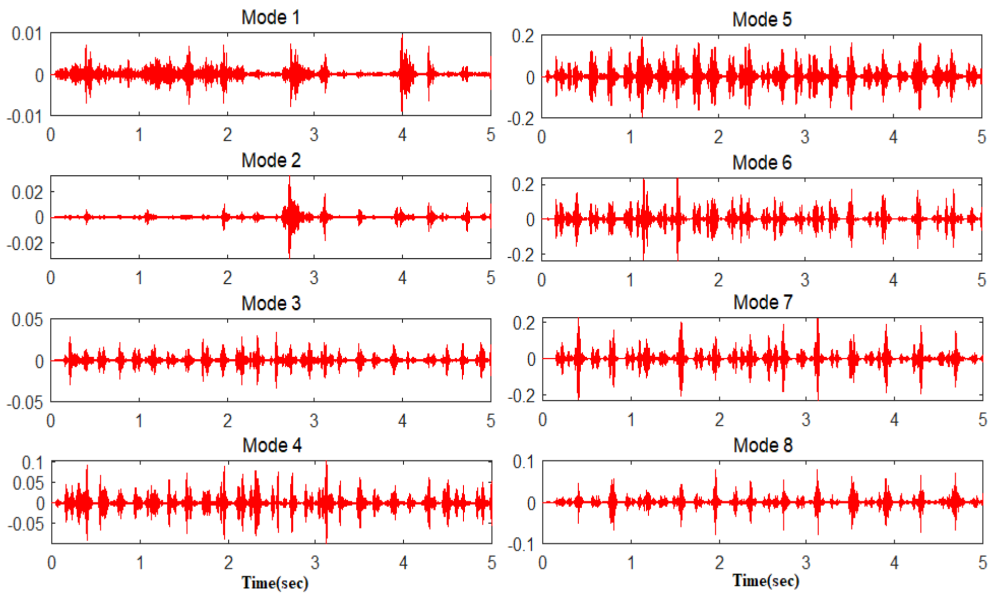


Fig 7. The decomposed sub signals (modes) of 2st VMD algorithm applied against the denoised PCG

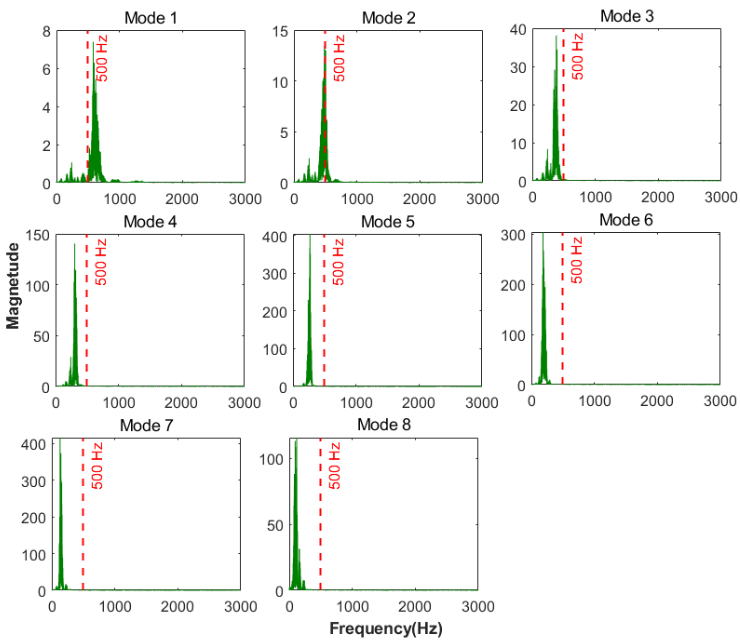


Fig 8. Frequency spectrum of each sub signal (mode) generated 2st VMD algorithm

From Fig.7 and Fig.8 it is clearly observed that mode 1 and 2 are high frequency sub signals and they are not relevant to useful heart sounds. Rest all the modes numbered from 3 to 8 overlaid in high frequency to low frequency order as shown in Fig. 8. From this figure it is clearly observed that mode 3, and mode 4 and mode 5 can be combined to form fetal PCG waves, while mode 6, mode 7 and mode 8 are combined to form maternal PCG waveforms. Eventually, Fig 9 represents the maternal PCG and fetal PCG produced as the end results of the proposed framework. The respective frequency spectrums of maternal and fetal PCGs are also shown in Fig. 9. The demarcation frequency line labelled with 250 Hz clearly distinguishes the maternal PCG and fetal PCG. Hence, the proposed framework efficiently decomposes and denoises the raw PCG signal and separates the maternal and fetal PCG components with promising accuracy.

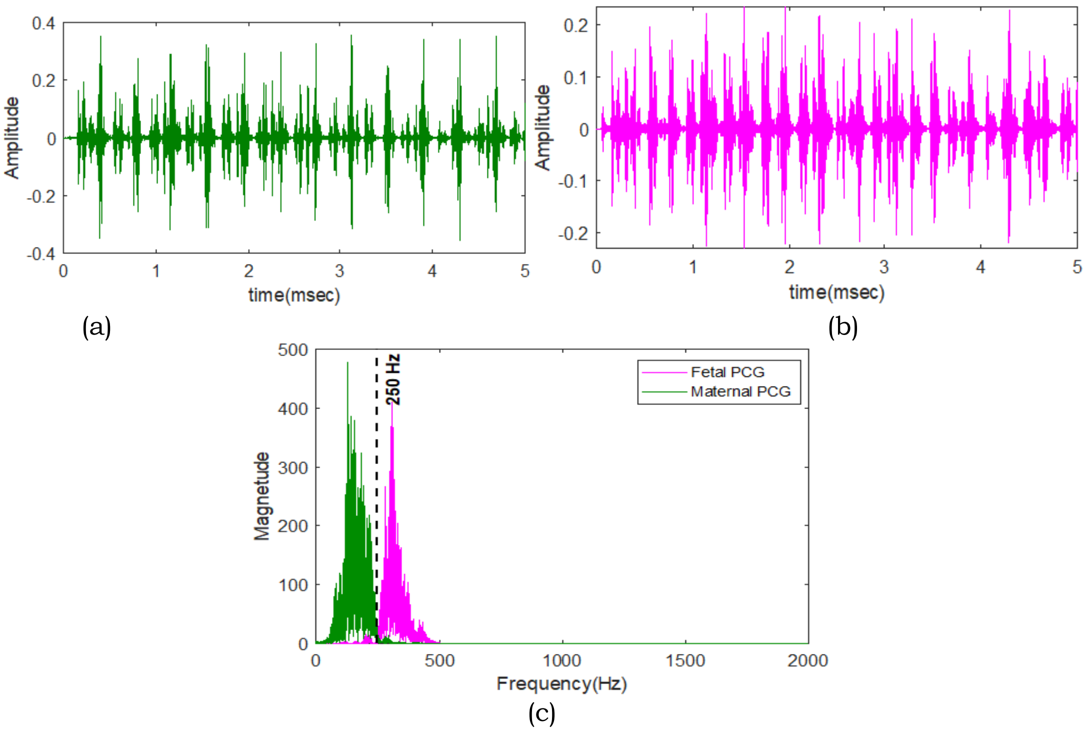


Fig 9. (a) Maternal PCG extracted by combining mode 3, mode4 and mode 5. (b) fetal PCG signals extracted by combining mode 6, mode 7 and mode 8. (c) Frequency spectrum of maternal and fetal PCG signals

Conclusion

Based on the analysis and discussion made in the preceding sections, the present study imparts the following concluding remarks: The denoising and separation of maternal and fetal PCG signals are accomplished using Variational mode decomposition algorithm. The efficacy of the framework is tested by applying two highly popular and publicly available fPCG databases obtained from online sources. Further, the entire fPCG processing was accomplished in two phases. In the first Phase, denoising mechanism is implemented using 1st stage of VMD algorithms; In the second Phase, the maternal and fetal PCG components are separated and displayed using 2^{nd} VMD algorithm. This study proved that, fPCG extraction using VMD is reliable and yields commendable accuracy and hence it is asserted as a suitable technique for efficient fPCG extraction and analysis. With the detailed refinement, the present framework can aid the medical experts, doctors and clinicians to observe the characteristics of fetal PCG waveform, assess the mother and fetus heath status, diagnose the cardiac abnormalities and monitor the heart functionality.

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