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# Simulation of the Generation and Processing of Doppler Ultrasound Fetal Heart Signals to obtain Directional Motion Information

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***Abstract*- In fetal heart monitoring using Doppler ultrasound signals the cardiac information is commonly extracted from non-directional signals. As a consequence often some of the cardiac events cannot be observed clearly which may lead to the incorrect detection of the valve and wall motions. Here, directional signals were simulated to investigate their enhancement of cardiac events, and hence provide clearer information regarding the cardiac activities. First, fetal Doppler ultrasound signals were simulated with signals encoding forward and reverse motion then obtained using a pilot frequency. The simulation results demonstrate that the model has the ability to produce realistic Doppler ultrasound signals and a pilot frequency can be used in the mixing process to produce directional signals that allow the simulated cardiac events to be distinguished clearly and correctly.**

## I. Introduction

Detection of cardiac movements is necessary to examine the functionality of the fetal heart and hence fetal health. Often, non-directional signals are used to extract fetal cardiac information and determine the fetal heart rate [1-3]. Using these signals, some of the cardiac events are not apparent and the events may not be detected accurately. It is possible that some of these problems may be overcome by using directional signals.

There are several ways of producing directional Doppler signals. The most widely used is to extract directional information by phase-shifting the in-phase, I and quadrature signals, Q obtained from quadrature demodulation and then adding the un-shifted signals with the shifted signals. Another technique is to use a pilot frequency in the mixing process (i.e. superheterodyne detection). In this technique, the forward and reverse signal frequencies are down converted to (intermediate frequencies) around the pilot frequency. This technique requires an additional oscillator that will add complexity to the circuit, but does not need quadrature demodulation. Use of a pilot frequency in this manner has previously been applied to the monitoring of arterial blood flow using ultrasound [4, 5].

## II. Model of Fetal Doppler Ultrasound Signals and Directional Processing

In Doppler ultrasound fetal heart rate monitoring, signals from the fetal heart are obtained by transmitting ultrasonic waves towards the fetal heart through the maternal abdomen. Signals reflected from the fetal heart and subsequently detected are a combination of signals from various parts of the heart. Each received signal experiences a delay due to the outward and return path of the ultrasonic waves. This total return signal can be written as

$$R(t) = A\sum_{n=1}^{N}\cos(\omega_c t - \theta_n(t)) \tag{1}$$

where $\theta_n(t) = \frac{2\omega_c s_n(t)}{c}$, $\omega_c$ is the carrier frequency (in radians per second), $c$ is the velocity of sound in human tissue, $s_n(t)$ is the distance between the transducer and each reflecting surface, N is the number of reflectors and, $A$ is the amplitude.

The received signal can be down converted to an intermediate frequency signal by first mixing it with a signal from an oscillator which has frequency that is different from the carrier frequency. The difference between the carrier and the oscillator frequency is called the pilot frequency. For simplicity, consider only a return signal from one reflector. Mixing the return signal with a cosine signal and then low pass filtering yields the in-phase signal, $I(t)$.

$$I(t) = \frac{AD}{2}\cos\left[\omega_p t - \theta(t) - \phi_{LO}\right] \quad (2)$$

where $D$ is the amplitude of the local oscillator signal and $\omega_p$ is the pilot frequency and $\phi_{LO}$ is the phase of the local oscillator.

The frequency baseline of the baseband signal has been shifted to that of the pilot frequency. Using this approach Doppler signals relating to forward and reverse motions are represented by frequencies above and below the pilot frequency and so can be isolated independently via filtering. Frequency shifting is then performed to extract the conventional directional signals that can be used to determine fetal heart rate.

## III. Computer Simulation of Directional Signals

In order to verify that this approach functions as expected, a simulated return signal was created using (1). A carrier frequency of 1.5 MHz was used with the local oscillator frequency set to a frequency which is 1 kHz difference from the carrier frequency. This local oscillator frequency was chosen to obtain an intermediate frequency of 1 kHz. The displacement data (i.e. $s_n(t)$ in (1)) used to form this signal produces a maximum Doppler shift frequency that is estimated to be 550 Hz.

To obtain the I signal, the received signal was first down converted to 1 kHz by mixing it with the cosine signal from the local oscillator. The resultant signal was then filtered using a low pass filter with a cut-off frequency of 1.55 kHz. Fig. 1 shows the spectrum of the resultant signal after this low pass filtering. Note that the pilot frequency (1 kHz) is located between the positive and negative frequency components of the signal.

The forward and reverse signals were extracted from the I signal obtained after mixing. To obtain the forward signal, this I signal was first filtered using a low pass filter with a cut-off frequency of 1 kHz. Fig. 2A shows the spectrum of the forward signal after low pass filtering. The resultant signal was then frequency shifted by 1 kHz by mixing it with a 1-kHz signal to produce the forward signal shown in Fig. 3B. Note that four modeled cardiac movements namely mitral valve opening, $M_o$, atrial wall contraction, $A_{wc}$, ventricular wall contraction, $V_{wc}$, and aortic valve opening, $A_o$, can be extracted from the forward signal. These events were identified by referring to the input displacements (i.e. functions $s_n(t)$). On top of Fig. 3 is the I signal that contains eight cardiac events.

The reverse signal was obtained by filtering the I signal using a bandpass filter with a cut-off frequency of 1 – 1.55 kHz and frequency shifting. Fig. 2B shows the spectrum of the reverse signal after bandpass filtering and Fig. 4B shows the reverse signal obtained after frequency shifting. Note that in the reverse signal, only the valve closure and wall relaxation events can be observed with the corresponding valve opening and wall contraction events apparent in the forward signal.

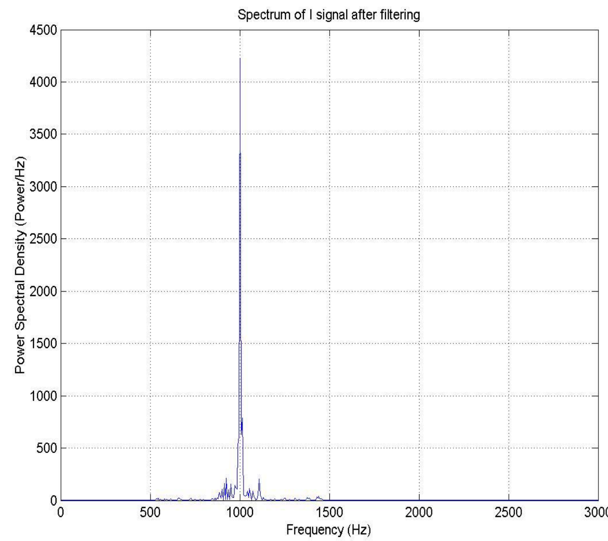


Fig. 1. Diagram showing the spectrum of I signal after passing through a low pass filter with cut-off frequency of 1.55 kHz.

To separate the valve and wall motions and to further enhance the cardiac movements, the forward and reverse signals were divided into two frequency ranges, 75 – 235 Hz and 400 – 550 Hz the intention being to separate the higher frequency 'valve' motions from those from 'wall' movement. (It should be noted that to reach their maximum higher velocities, the valves must accelerate through the 'wall' velocity, and hence, frequency range and so will make a contribution to the 'wall' signals). Fig. 3C and Fig. 4C show the wall signals obtained from the forward and reverse signals respectively. The valve signals are shown in Fig. 3D and Fig. 4D. Note that as anticipated at the start and end of valve motion a contribution to the 'wall' channel appears. Results from this simulation certainly show that separating forward and reverse signals offers the potential to produce clean signals that may enable the extraction of cardiac timing information.

Note that it is the final bandpass filtering operation that produces wall and valve signals that have the same appearance (see Fig. 3C, Fig. 3D, Fig. 4C and Fig. 4D) as what are conventionally shown as typical Doppler ultrasound signals. This indicates that the model used in this simulation is capable of producing quasi-realistic signals and that the characteristics of the final bandpass filter (that can be considered in part to act as a frequency to 'voltage' converter) influence the final signal's characteristics.

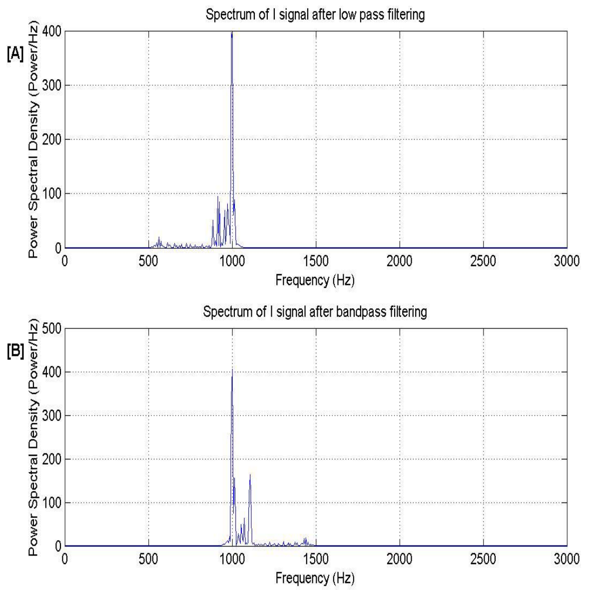


Fig. 2. Diagram showing the spectrum of forward and reverse signals after the I signal is passed through [A] a low pass filter with a cut-off frequency of 1 kHz [B] a 1 - 1.55 kHz bandpass filter.

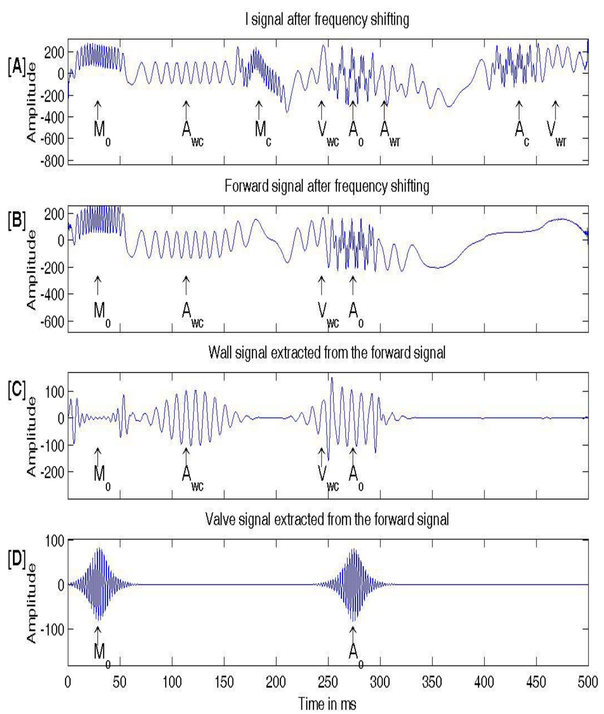


Fig. 3. Diagram showing cardiac motions and signals extracted from the forward signal [A] The I signal [B] The forward signal [C] Wall signal [D] Valve signal. Note: $A_{wc}$ - atrial wall contraction, $A_{wr}$ - atrial wall relaxation, $V_{wc}$- ventricular wall contraction, $V_{wr}$ - ventricular wall relaxation, $M_o$ - mitral valve opening, $M_c$ - mitral valve closure, $A_o$ - aortic valve opening and $A_c$ - aortic valve closure.

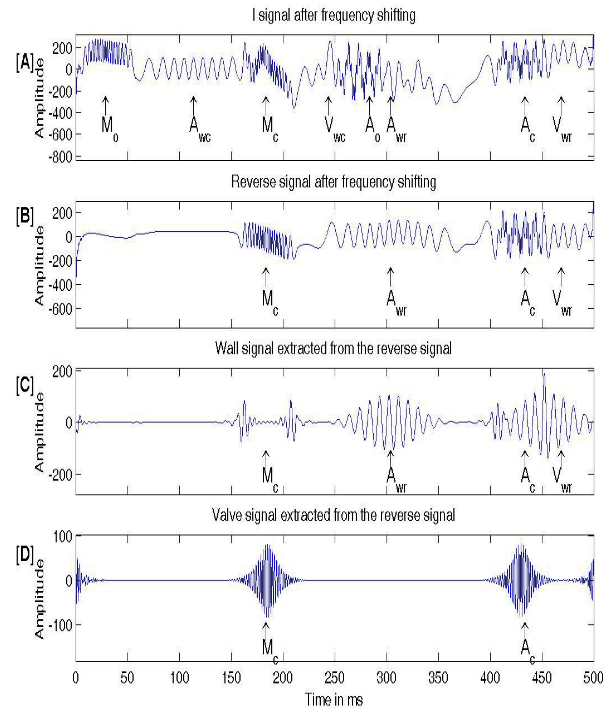


Fig. 4. Diagram showing cardiac motions and signals extracted from the reverse signal [A] The I signal [B] The reverse signal [C] Wall signal. [D] Valve signal. Note: $A_{wc}$ - atrial wall contraction, $A_{wr}$ - atrial wall relaxation, $V_{wc}$ - ventricular wall contraction, $V_{wr}$ - ventricular wall relaxation, $M_o$ - mitral valve opening, $M_c$ - mitral valve closure, $A_o$ - aortic valve opening and $A_c$ - aortic valve closure.

## IV. Discussion

The simulation results shown above provide evidence of the ability of the proposed model to produce realistic fetal Doppler ultrasound signals and the simulation of the use of a pilot frequency to obtain directional signals. This demonstrates that separating the forward and reverse signals enhances the signals associated with cardiac events. The model also demonstrates how the final bandpass filter acts as a frequency to voltage converter to produce a signal whose envelope relates to the cardiac motion. In this simulation, the forward and reverse signals were obtained from the I signal only via the use of a pilot frequency. Alternatively, combination of I and Q signals could be used to produce the directional signals [6]. The advantage of using one non-directional signal is that only one mixer is required, the disadvantage is the need for a local oscillator with a frequency that differs from that of the generated ultrasound.

## V. Conclusion

The model of the Doppler ultrasound return signal from the fetal heart presented here can be used to generate realistic signals for evaluating new processing techniques. It has been shown how using a pilot frequency in the mixing process can produce directional signals that allow the fetal cardiac motions to be enhanced making their recognition less complex.

## REFERENCES


[1] T. Koga, N Athayde and B. Trudinger, "A new ultrasound technique to measure the isovolumetric contraction time as an index of cardiac contractility: fetal lamb validation*," J. Soc. Gynecol. Investig.*, vol. 10, pp. 194-199, 2003.

[2] R. N. Wolfson, I.E. Zador, S. K. Pillar, I.E. Timor-Tritsch and R. H. Hertz, "Antenatal Investigation of human fetal systolic timing intervals", *Am. J. Obstet. And Gynecol*., vol. 129, pp. 203-207, 1977.

[3] Y. Murata and C. B Martin, "Systolic time intervals of the fetal cardiac cycle", *Obstetrics and Gynaeclogy*, vol. 44, pp. 224-232, 1974.

[4] B. A. Coghlan and M.G. Taylor, *"On methods for preprocessing directional Doppler signals to allow display for directional blood-velocity waveforms by spectrum analysers"*, *Med. & Biol. Eng. & Comput.*, vol. 16, pp. 549-553, 1978.

[5] B. A. Coghlan and M.G. Taylor, "Directional Doppler techniques for detection of blood velocities", *Ultrasound in Med. & Biol*, vol. 2, pp. 181-188, 1976.

[6] N. Aydin and D.H. Evans, "Implementation of directional Doppler techniques using a digital signal processor", *Med. & Biol. Eng. & Comput.,* vol. 32, pp. S157-S164, 1994.