BLOOD AND WALL SIGNAL SIMULATOR FOR DOPPLER ULTRASOUND SIGNAL ANALYSIS ALGORITHM DEVELOPMENT

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Abstract- Doppler ultrasound instruments, used for the detection and monitoring of vascular disease, require a means of separating the large, low frequency Doppler signal from the vessel wall from the signal arising from blood followed by a means of analysing the blood flow signal in order to characterise the flow conditions. This is normally achieved by using a high-pass filter that removes the signal reflected from the vessel wall. Unfortunately, the filter also removes the low frequency Doppler signals arising from slow moving blood. A better signal segmentation method that reduces the loss of signal from slowly moving blood is needed to permit the measurement of lower blood velocities. A signal simulator that generates Doppler signals that include the contributions from blood and vessel wall will be very useful for the development of new Doppler signal segmentation methods. This work presents a new simulator incorporating the contribution of blood and vessel wall movements; the characteristics of the simulator output signal are similar to those found in practice.

Keywords – Doppler, ultrasound, blood, flow, simulation

I. INTRODUCTION

Cardiovascular disease leading to heart attacks and embolic strokes amongst others is a leading cause of death and severe disability in the population of the so-called "developed world". The disease is characterised by plaque on the walls of arteries, disturbing the flow of blood, creating vortices and turbulence. This disturbed flow is often used as an indicator of the presence of disease and quantifiers of disturbance are used to monitor disease or treatment. More sensitive techniques capable of detecting small degrees of flow disturbance in the slowly moving blood close to the vessel wall are needed in order to improve the efficiency of diagnosis and the outcome of medical treatments. In addition, it has long been recognised that flow conditions close to the vessel wall have an influence on disease initiation and growth and researchers in this area have an interest in the measurement of the low blood velocity in this region.

A popular instrument for non-invasive blood velocity estimation is the pulsed ultrasonic Doppler blood flow detector which determines blood velocity by measuring the Doppler shift in the frequency of ultrasound scattered by moving red blood cells flowing through a small volume (the 'sample volume') within a thin ultrasound beam projected through the blood vessel from a transducer placed on the skin surface. The output of the instrument is a signal (the Doppler signal) in the audio frequency range whose frequency spectrum reflects the range of blood velocities within the sample volume. Flow disturbance results in an increase in the Doppler spectrum width which is used to detect atherosclerotic lesions in arteries. The resolution of the spectral estimator used limits the detection sensitivity of disturbance-induced spectral broadening.

The Doppler signal is complex. Since the ultrasound is scattered from a random distribution of blood cells the Doppler signal from blood is random. Since the blood flow in arteries is pulsatile the blood velocity and therefore the Doppler signal spectrum varies during each cardiac cycle. In addition, ultrasound scattered from the pulsating vessel wall also gives rise to a low frequency Doppler signal with an amplitude orders of magnitude higher than the signal from blood.

Commercially available Doppler instruments usually remove the signal reflected by the vessel wall with a high-pass filter. Unfortunately this filter also removes the low frequency Doppler signals arising from slow moving blood, including that close to the vessel wall.

There is a need for a method of signal segmentation - separating the signals from blood and wall - that reduces the loss of signal from slowly moving blood and therefore permits the measurement of lower blood velocities.

Much work has been carried out to investigate methods of separating blood and wall signals and computer simulations/models of the signals from wall and blood have been valuable in the development of signal processing algorithms– for example [1-3]. However, although the simulations/models of Doppler signals from blood have been developed over many years and have characteristics very similar to real signals [4-11] wall signal models are relatively crude – single sinusoids or random signals. A simulator is required that generates a Doppler signal as from blood and vessel wall, having controllable characteristics similar to those found in practice.

II. METHOD

An overview of the method is shown in Fig.1. A transmission line model of the lower limb arterial tree using the electrical circuit simulation software SPICE has been developed

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Abstract

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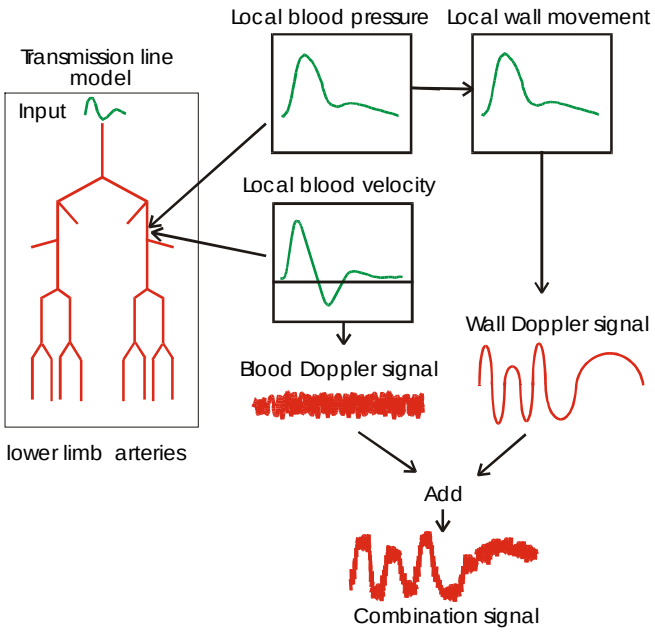

Fig. 1 Method of combined blood/wall Doppler signal generation.

giving the local blood pressure (voltage analogue) and blood flow (current analogue) waveform at any arterial segment within the tree [12-13]. The radial vessel wall displacement waveform is calculated from the pressure waveform and the Doppler signal may be calculated from the wall velocity and wall/ultrasound-beam geometry. The Doppler signal from blood may be calculated using the blood velocity information and vessel/beam geometry. The two signals may then be summed to give the combined Doppler signal.

For this first attempt at generating a quasi-realistic signal some simplifying limitations and approximations have been imposed. For the wall signal, the ultrasound beam position is restricted such that the beam axis intersects the vessel axis and to a sufficiently small width compared with the vessel diameter that the wall within the beam may be considered plane. The signal from the wall is also considered as arising from a single scattering surface. The wall is also considered elastic so that the wall displacement is proportional to the local blood pressure. The blood Doppler signal spectrum variation through the cardiac cycle is assumed to be dominated by the variation in spectral mean frequency variation which in turn is proportional to the blood velocity variation and the spectral width is kept constant.

The method of generating a blood Doppler signal under the above conditions from a blood velocity waveform has been described previously [9]. Briefly, the complex signal (the in-phase and quadrature signals) is given by:

$$s_b(t) = a_b r_b(t) \exp\left(j2\pi \int_0^t f_m(\tau) d\tau \right) \quad (1)$$

where a_b is an amplitude constant, $r_b(t)$ is a zero mean, unit standard deviation, Gaussian variable with constant bandwidth centred on zero frequency and f_m is the mean frequency variation through the cardiac cycle related to the blood velocity $v(t)$ by:

$$f_m = \frac{2v(t) f_o \cos(\theta)}{c} \quad (2)$$

where θ is the beam/vessel angle, f_o is the transmitted frequency and c (1540m/s) is the ultrasound propagation speed.

The wall signal is generated by calculating the wall displacement followed by the phase variation along the ultrasound beam and then the Doppler signal. The relationship between blood pressure (P) and radial wall displacement (R) is given by [14]:

$$\frac{dR}{dP} = \frac{1.5 R_i^2 R_o}{E\left(R_o^2 - R_i^2\right)} \quad (3)$$

where, E is the wall elastic modulus, R_i is the vessel internal radius and R_o the external radius. The component of wall displacement along the ultrasound beam is then:

$$x_d(t) = \frac{dR}{dP}\left(P(t) - \overline{P}\right)\sin\theta \quad (4)$$

where $P(t)$ is the pressure waveform and $\overline{P}$ is the mean pressure. The phase variation in the reflected ultrasound, since a movement of $\lambda/2$ along the beam increases the round trip path by λ and the phase by 2π, is then:

$$\phi_d(t) = 2\pi \frac{x_d(t)}{\lambda/2} = 4\pi \frac{x_d(t) f_o}{c} \quad (5)$$

and the wall Doppler signal is:

$$s_w(t) = a_w \exp\left(j\phi_d(t)\right) \quad (6)$$

The combined Doppler signal is then given by:

$$s(t) = s_b(t) + s_w(t) \quad (7)$$

with a blood-to-wall signal ratio *of* $20 \log_{10}(a_b/a_w)$ dB.

III. Test and Results

In order to test the simulator, Doppler signals were generated using the equations (1-5) with inputs of the pressure and blood velocity waveforms from the common femoral artery of the transmission line model [12-13] with $E = 4\times10^5 \mathrm{Nm}^{-2}$, R_i=0.27cm, R_o=0.323cm and ultrasound characteristics f_o = 5MHz, c =1540ms^{-1} and θ = 60°, the Doppler signal from the blood was simulated with a constant rms bandwidth of 800Hz. The composite signal was then filtered by a 4-pole Butterworth high-pass filter with 3 dB cut-off frequencies of 10, 40 and 200Hz as would be typical for the

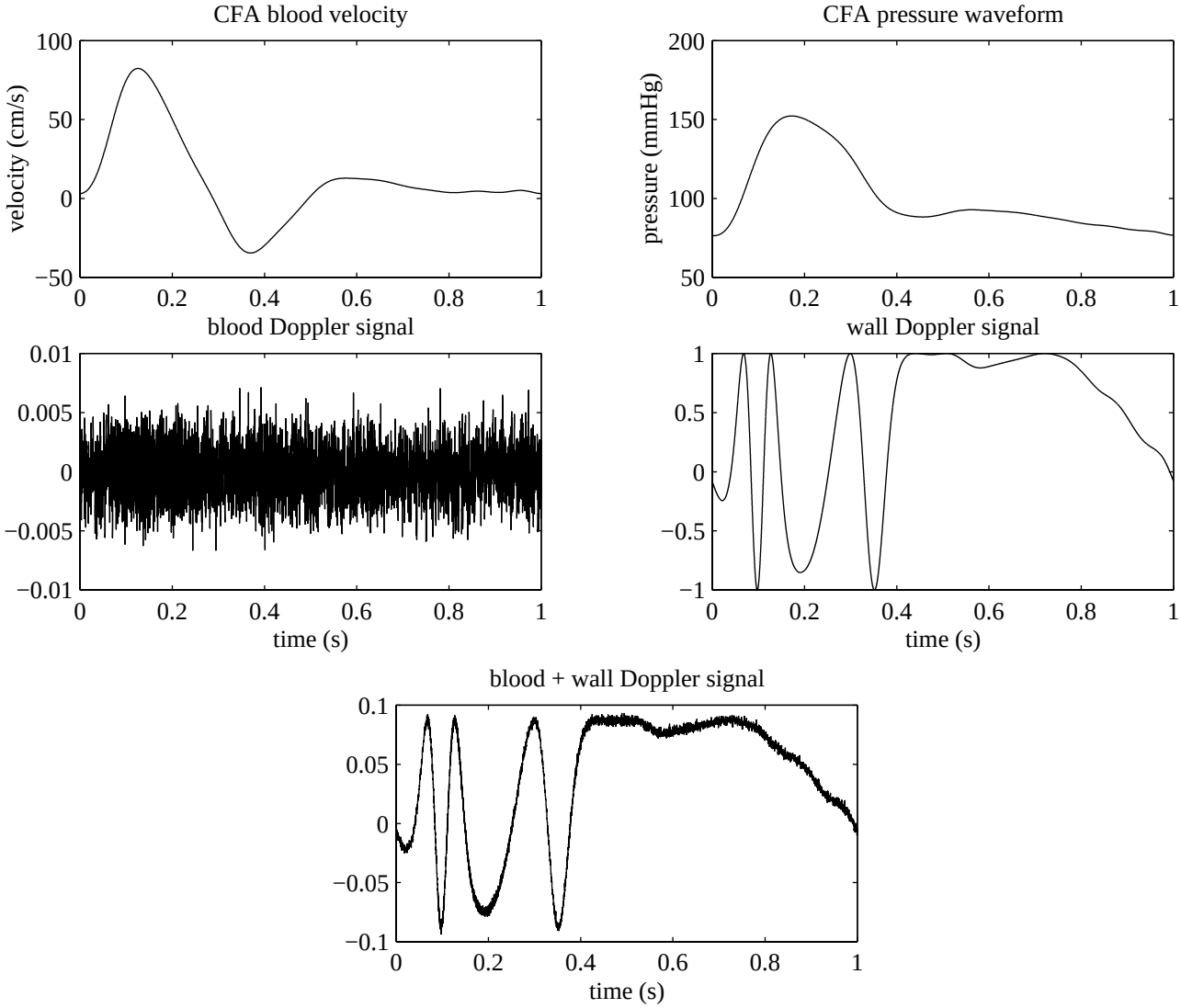

Fig. 2- The input waveforms and the output signals (from left to right and top to bottom): the common femoral artery (CFA) blood velocity waveform; the common femoral artery pressure waveform; the simulated in-phase Doppler signal arising from blood flow; the simulated in-phase Doppler signal produced by the vessel wall movement; and the composite (blood +wall) in-phase Doppler signal for a 30dB wall-to-blood signal ratio.

'wall-thump' filter of a Doppler ultrasound instrument. The wall-to-blood signal ratio of the simulated composite signal was 30dB and the signal was clipped to 4 times the root mean square amplitude of the blood signal.

The blood velocity and pressure waveforms and corresponding blood, wall and composite Doppler signals are shown in Fig. 2.

The spectrograms of the high-pass filtered signals with spectrogram characteristics of 7.8ms, Hanning window with 50% window overlap are shown in Fig. 3.

IV. Discussion

The composite Doppler signal has a similar form to that observed in Doppler ultrasound instruments with the noise-like blood Doppler signal superimposed on the lower frequency high amplitude Doppler signal from the wall. The wall signal frequency is highest during the systolic rise and fall periods of the pressure pulse. The spectrograms show the blood flow spectrum with the low frequency vessel wall 'thump' signal 'breaking through' when the filter cut-off frequency is low and being removed by the filter with the higher cut-off frequency. The simulator clearly has the characteristics required.

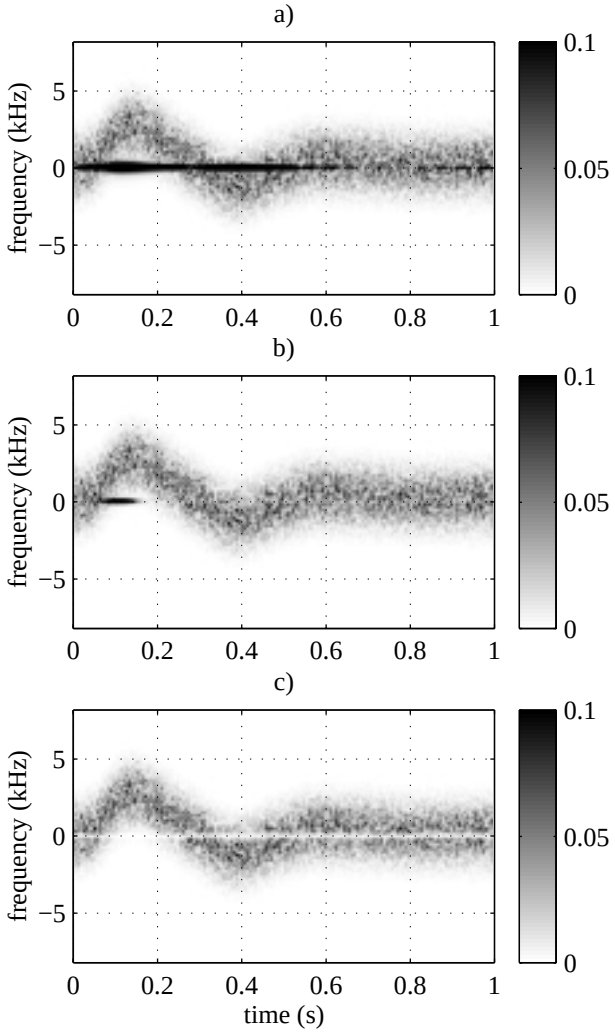

Fig. 3- Spectrograms of composite (blood + wall) simulated Doppler signal filtered with a 4 pole Butterworth high-pass filter with the following cut-off frequencies: a) 10 Hz; b) 40 Hz; and c) 200 Hz.

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