ULTRASONIC BLOOD FLOW SENSING USING DOPPLER VELOCIMETRY

Michelle Case, Matthew Micheli, Daniel Arroyo, Jeremy Hillard, Martin Kocanda

College of Engineering and Engineering Technology

Northern Illinois University

Dekalb, IL 60115

Email: marko@niu.edu

Submitted: June 23, 2013 ***Accepted: Aug. 10, 2013*** ***Published: Sep. 3, 2013***

Abstract- Ultrasonic blood flow sensing is a non-invasive method for measuring blood flow velocity. The objective of this work is to produce a low-cost ultrasonic blood flow instrument utilizing Doppler shifted signals and enhanced signal processing methods. The instrument transmits a single-frequency signal into circulatory tissues and receives a signal that is Doppler shifted in proportion to velocity. Subsequent processing techniques produce an audio feedback signal whereby the user "hears" the flow characteristics. The circuit used consists of a transmitter, receiver, and frequency shifter. Signal processing is performed externally to produce velocity profiles of arterial blood flow using Matlab™ to create spectrograms and low-pass filtering on the recorded feedback signals. Spectrogram provide mapping of the velocity profiles. Resultant mapping indicate that velocity profiles have a roughly parabolic shape and that filtering is required to reduce high frequency noise. Signals were obtained using multiple cardiac stressors to determine the flow sensing performance.

Index terms*:* cardiac sensing, digital filters, Doppler Effect, Matlab™, signal processing, spectrogram, ultrasonic flow meter, velocimetry, velocity profiles.

I. INTRODUCTION

Measuring and understanding fluid flow has been an important concept in science and engineering. Bernoulli proposed that fluid flow conserves energy [1]. Doppler discovered that sound emits a different frequency if it moves toward or away from an object. This is the concept behind ultrasonic flow meters [1]. Ultrasonic flow meters are used in industry to measure fluid flow velocity. Particles in the fluid cause the frequency shift, which is used to measure velocity of liquids and gases. These meters have high accuracy, rapid response and are unaffected by pressure, temperature and viscosity variations [2].

Ultrasonic flow meters are used in the medical field because they are non-invasive. Blood flow correlates to the concentration of nutrients in the cells. Without blood flow readings, a doctor may use blood pressure, or an electrocardiogram (ECG) signal [3]. Blood flow is used to locate obstructions in flow. It can detect fatal diseases and monitor treatment techniques. Invasive flow meters are not often used because they can cause blood clots [3].

Ultrasonic blood flow meters obtain blood flow continuously. There are many variations of the Doppler ultrasonic blood flow meter including: the transit-time flow meter, continuous-wave Doppler flow meter, pulsed Doppler, and laser Doppler blood flow meter [3]. A transit-time flow meter obtains velocity by measuring the time difference between transmitted and received sounds. This method measures flow direction; however, an invasive surgery is required [3]. Continuous-wave Doppler flow meters use piezoelectric transducers to transmit and receive the sound waves [3]. The transmitted sound waves are beamed through tissue and used to measure blood velocity by detecting the Doppler shifted velocity. A pulsed Doppler flow meter acts as radar. It excites the transmitter and waits for the received signal. The velocity is obtained from varying delays, and this method requires one transducer. However, the calculations are more complicated [3]. Laser Doppler flow meters use lasers and the shift in light caused by red blood cells to determine flow [3].

Ultrasonic flow meters are expensive because of high frequency signal sources and signal processing techniques. The objective of this work is to implement a less expensive ultrasonic flow meter and to develop signal processing techniques that display arterial blood velocity. A procedure in Matlab™ was developed that could be applied to instrument that do not have display capability.

II. RELEVANT BACKGROUND

a. Doppler Effect

Ultrasonic waves are ideal for non-invasive sensing [2]. A moving object changes the frequency of sonic waves before and after it. The sonic waves compress before an object and spread out behind it. This frequency shift is the Doppler Effect [1]. Figure 1 illustrates the Doppler Effect.

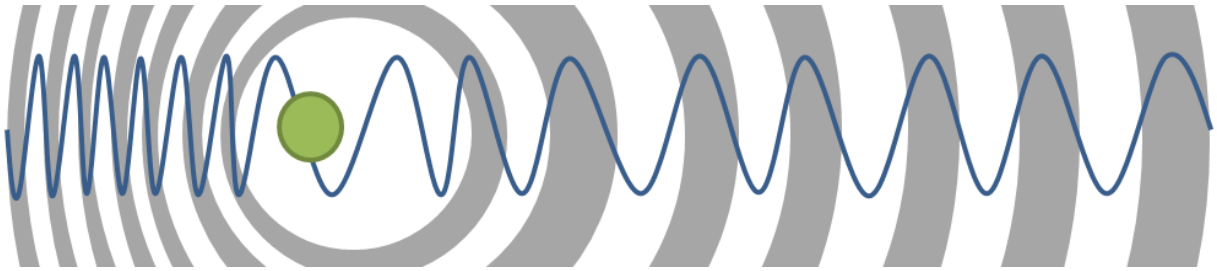

Figure 1. Doppler Effect

Ultrasonic flow meters obtain the Doppler frequency shift. These devices include a transmitter and receiver. Reflective material bounces the transmitted wave back into the receiver. The received wave has a frequency shift. The source frequency is lowered twice. The first shift occurs when the transmitted wave hits the object and the second shift occurs when the resulting wave comes back [3]. This can be seen in Figure 2. The angle between the transmitted wave and flow factors into Doppler frequency shifts [3]. The Doppler frequency can be calculated using the following equation:

_____ (1)

where is the Doppler frequency shift, is the source frequency, u is the velocity, θ is the angle factor, and c is the velocity of sound in the medium [3]. Doppler frequency is proportional to flow velocity, as seen in Equation 1. Rearranging the terms gives the following equation:

_____ (2)

The equation can be simplified if the angle is assumed to be irrelevant [4]. This assumption was applied since there was no method to measure the angle accurately. The following conversion factor relating velocity and the Doppler shifted velocity is:

— (3)

Equation 3 is the conversion factor used to change frequency to velocity. The velocity of ultrasound in human tissue is known to be in the range of 1540 m/s to 1600 m/s [4].

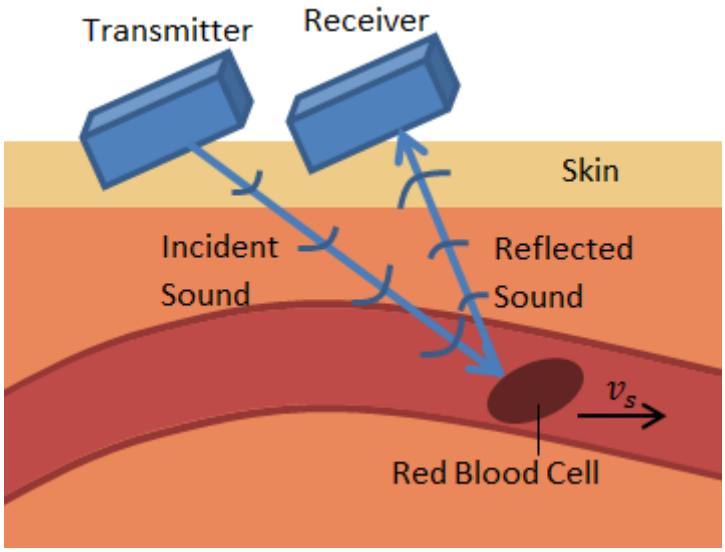

Figure 2. Ultrasonic flow meter using Doppler shift

b. Piezoelectric Transducers

Piezoelectric transducers transmit and receive ultrasonic waves. These transducers convert electric power to acoustic form [3]. The piezoelectric material is formed into discs and surrounded by metal electrodes. Electrodes are driven by an oscillator, which produces an up and down motion in the material. This motion creates longitudinal plane waves that propagate into tissue [3]. Ultrasonic waves are received using the same process, seen in Figure 3. Any gaps between the transducer and tissue need to be filled with a fluid or gel. Loss occurs because

ultrasonic waves do not travel well through air or gas. The gel ensures the ultrasonic waves transmit. Ultrasonic transducers operate in a frequency range of 2 and 10 MHz [4].

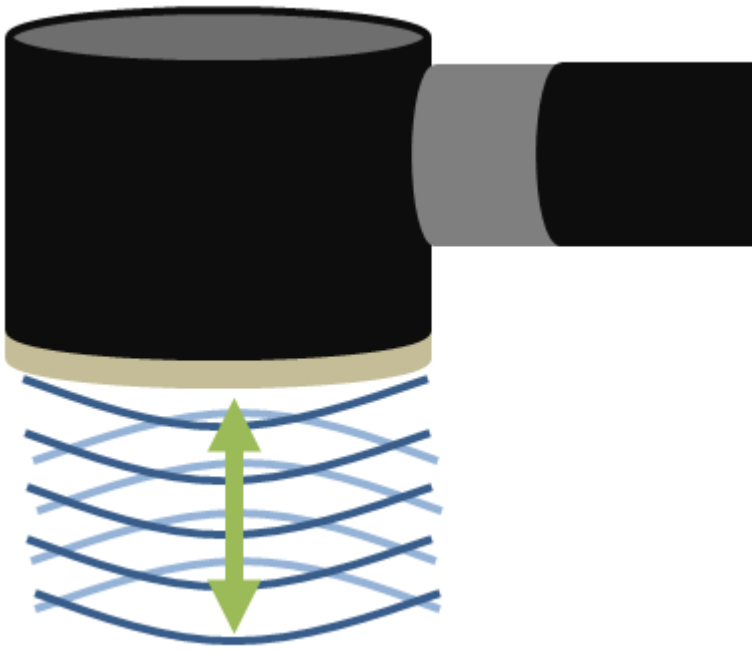

Figure 3. Piezoelectric transducers

c. Fluid Dynamics

Fluid kinematics is the study of fluid motion. There are two main reference planes. The Lagrangian reference plane focuses on an individual particle in the flow. The Eulerian reference frame focuses on a control volume and observes fluid flow as it goes by [1]. Mass flow rate can be solved for by applying the Reynolds transport theorem to the conservation of mass. The result after simplification with the assumption of uniform-steady flow is:

(4)

where is the mass flow rate, is the density of the fluid, V is the velocity of the fluid, and A is the area through which the flow is traveling [1]. Uniform flow implies that both the fluid density and velocity is constant over any area. Steady flow means the flow is not changing over time [1].

Equation 4 illustrates that if the area of a flow is reduced and mass flow rate is held constant, then the velocity will increase. This situation is similar to a blood clot.

Fluid dynamics models fluid flow in a blood vessel. A blood vessel can be modeled to a pipe system. There are two types of flow in a pipe system. Laminar flow is fully developed flow that is layered and ordered. Turbulent flow has velocity fluctuations and disordered motion. Viscosity is the internal resistance to flow or the relationship between shear stress and the time rate of strain. A no slip boundary condition exists when a fluid is touching a surface. This condition assumes the fluid touching the surface must move at the speed of the surface. The edges of a pipe are not moving. This means the fluid velocity touching the wall is zero. As the viscosity is reduced the fluid moves faster. Shear stress has a linear profile for Newtonian fluids because the coefficient of viscosity is constant [1]. Pipe systems have two non-moving boundaries, so the velocity profile of laminar flow is parabolic, seen in Figure 4. Assuming a parabolic velocity profile allows the maximum velocity method to be used, which assumes the mean velocity is half the maximum velocity [5]. This method can be applied to blood flow.

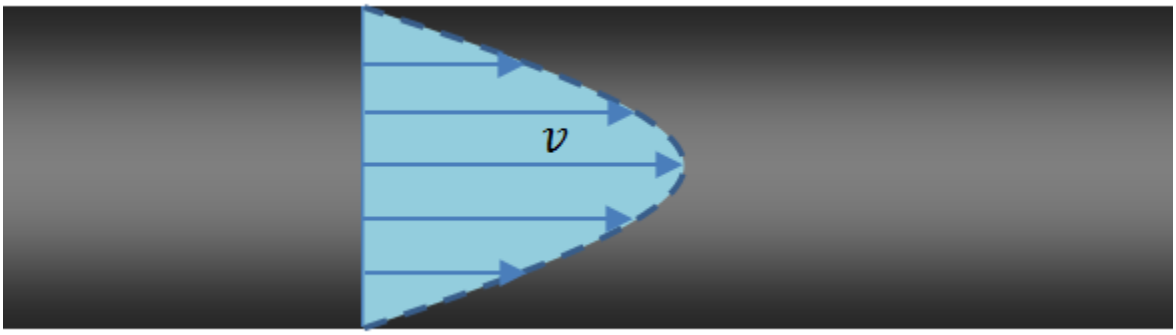

Figure 4. Velocity profile of laminar flow in pipe

d. Arterial Blood Flow

Arterial flow is blood flow in arteries. Arterial flow pulses and is not constant. This corresponds to a rise in pitch from the audio signal produced from a flow meter, followed by one or more smaller waves. This is caused by under-damped flow conditions. The flow meter output makes the velocity profile look like a full-wave rectified signal [3]. An example of how blood velocity over time in the aorta looks is in Figure 5 [6]. The velocity profile in arterial flow is similar to a

parabola. Blood velocity in humans is between 20 mm/s and 750 mm/s. Blood flows faster in arterial flow. Arterial flow was measured in this study.

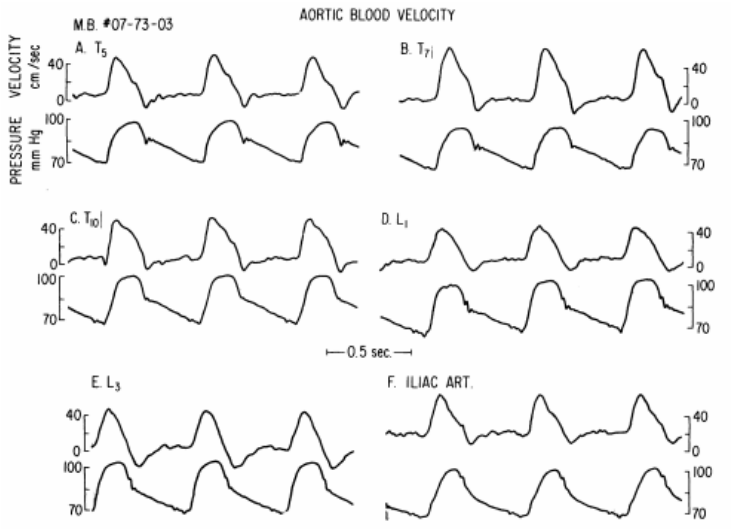

Figure 5. Velocity and pressure measurements in aorta [6]

e. Spectrograms

Spectrograms display blood velocity from ultrasonic blood flow meters. A spectrogram is a plot of frequency over time. The spectrogram is found by taking the Fourier transform (FT) of a small data segment. The data is windowed or separated into sections. A FT is taken for each window [7-9]. Windows are overlapped to prevent data loss. The spectrogram displays signal strength by color intensity. An example of a spectrogram is shown in Figure 6.

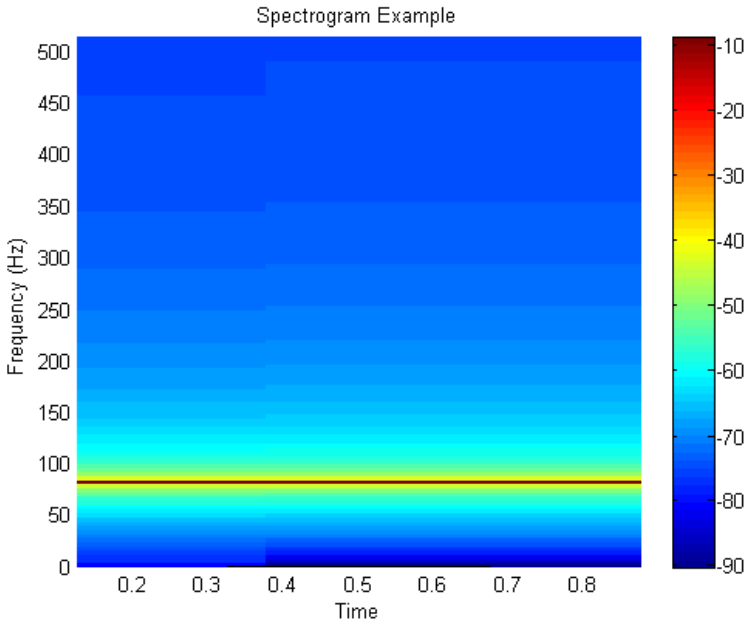

Figure 6. Spectrogram example

Interpreting spectrograms is not difficult. In the case of Figure 6, the red color represents a strong signal. An 80 Hz signal can be seen. Spectrograms display blood velocity profiles in this study.

III. DESCRIPTION OF DESIGN

a. Circuit

The circuit for the ultrasonic blood flow meter has three main parts. The circuit construction was based off another design with a few modifications. The whole circuit is displayed in Figure 7. The circuit has a signal generator chip (XR-2206) that is connected to provide a 400 KHz signal. This is the source frequency. This is lower than ultrasonic frequencies for medical equipment to reduce cost. The lower frequency means the ultrasonic waves cannot penetrate deeply into the body, but the sound waves can still reach blood vessels close to the skin's surface. The 400 KHz signal is amplified before going to the transmitting transducer.

The receiving transducer sends its signal to an operational amplifier to increase the gain. The signal from the receiver and the signal from the transducer are mixed using a multiplier chip (AD633JN). Mixing the two signals, or multiplying them, produces two signals, as seen in Equation 5, where f_0 is the transmitted frequency and Δf is the Doppler shifted frequency.

$$\cos(f_0+\Delta f)\times\cos(f_0)=1/2\ \cos(2f_0+\Delta f)+1/2\cos(\Delta f) \quad (5)$$

One of these signals is a sinusoidal signal with the Doppler shifted frequency. This is the signal needed to find velocity. The new signal is the audio output. This allows the Doppler shifted frequency to be recorded.

The Doppler shifted frequency is low, usually under 400 Hz. The frequency shifter generates a 500 Hz signal and then mixes this signal with the 400 KHz signal. This shift is done before it is mixed with the receiving signal. The 500 Hz shift allows the signals to center around 500 Hz instead of zero. This shift is beneficial because it shifts the Doppler frequency to a higher value which is easier to detect in the spectrograms and allows low frequency noise to be filtered out without signal distortions. Transmitting and receiving probes were constructed using piezoelectric transducers.

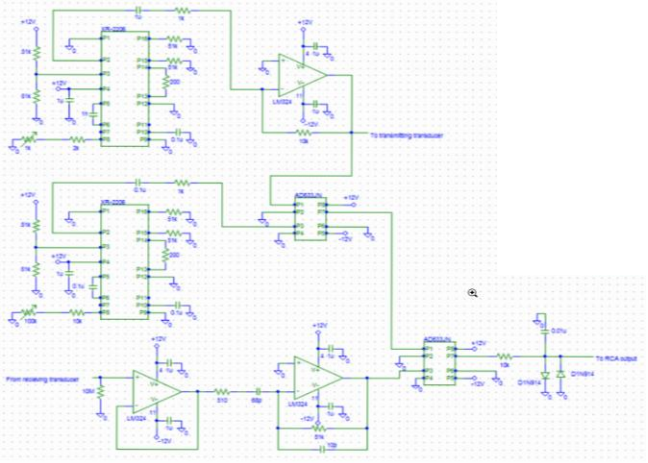

Figure 7. Schematic of ultrasonic blood flow meter

b. Signal Processing Design

The outputted audio signals were processed in MATLAB. Figure 8 shows the design process for the signal processing. The green boxes indicate the steps used. The red boxes indicate the steps tried and deemed inferior.

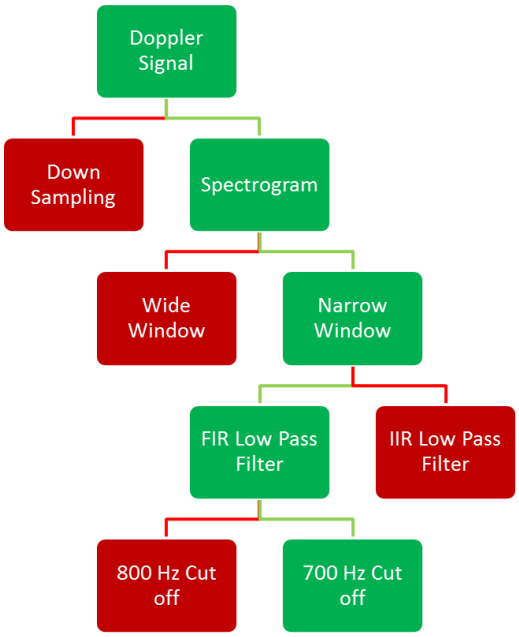

Figure 8. Signal processing design

The sampling frequency was 44,100 Hz. Down sampling was implemented, but this process distorted the signal and many details were lost. The Doppler shifted frequency is a time independent signal. Down sampling removed too many details. Spectrograms were used to show the velocity profiles. Two different window lengths were tested to determine which method gave better results. A similar process was used to determine which low pass digital filter should be implemented as well as the corresponding cut off frequency for that filter.

IV. MEASUREMENT METHODS

Testing was done to receive arterial flow from the heart. Gel was applied to both of the probes being used and the skin where the probes were being applied. This was done to ensure no air gaps existed. The probes were placed below the left-sided ribs. The subject of the test was lying down on a bed to record a resting heart rate. The RCA output was connected to speakers to hear the flow sensor's tone. The signal was located when the tone changed with time. The speaker output was connected to a laptop, and the audio was recorded using free software called Audacity. Figure 9 shows the set up for the flow meter. Figure 10 shows the wire connections, and Figure 11 shows the Audacity software.

Figure 9. Set up for ultrasonic flow meter testing

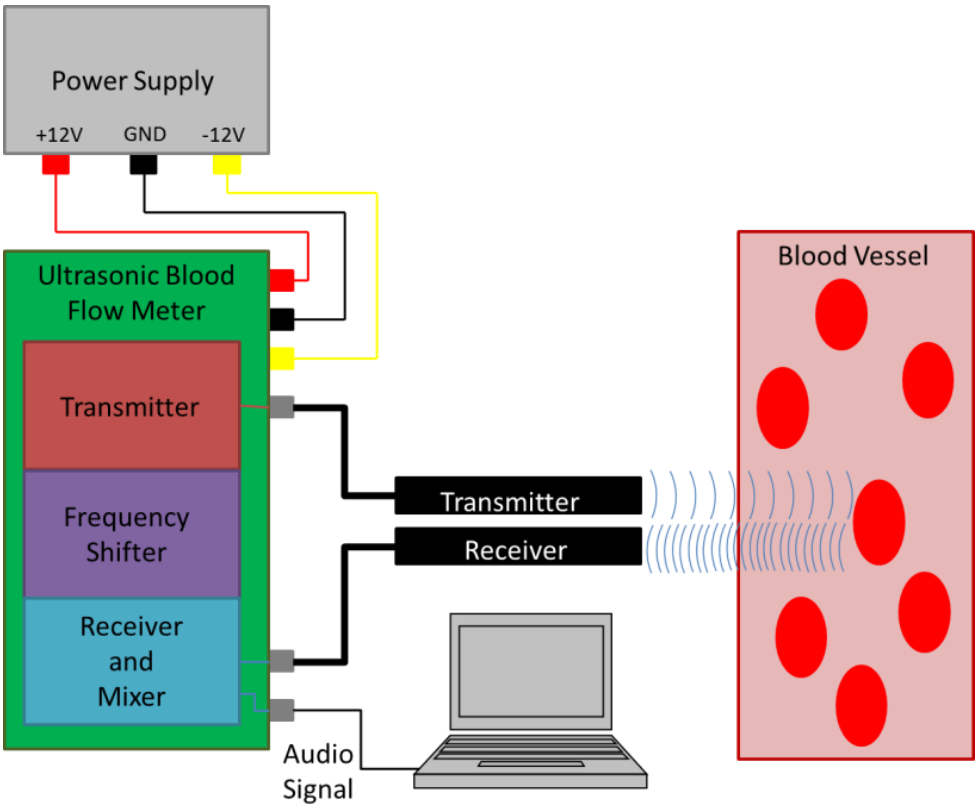

Figure 10. Flow meter connections and set up

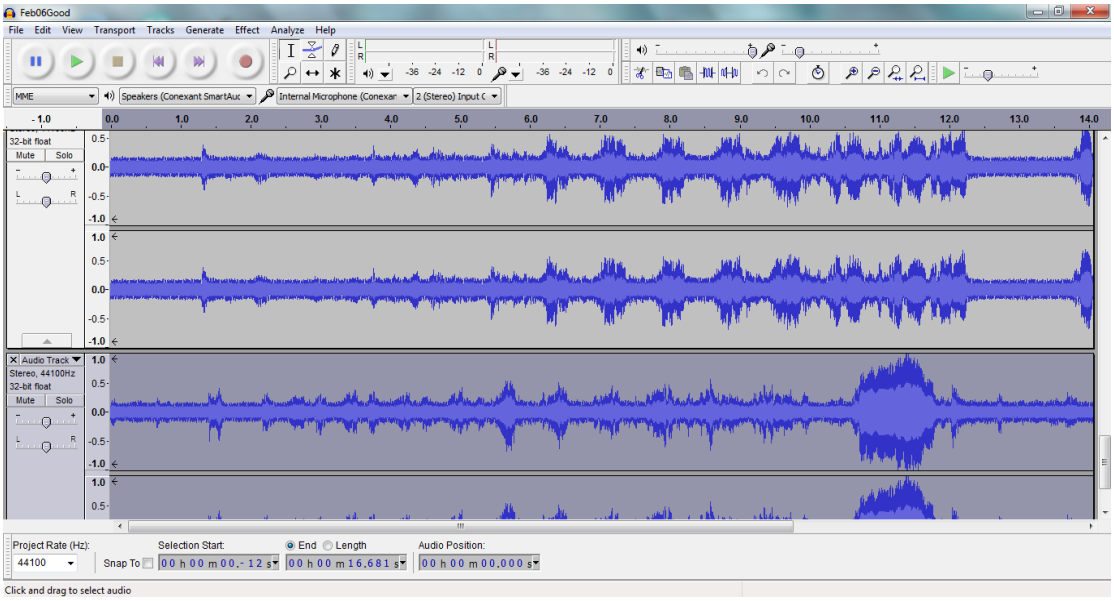

Figure 11. Example of recordings using Audacity software

V. MEASURED RESULTS

The recorded heart blood flow signals were imported into MATLAB and displayed, seen in Figure 12. The signal oscillations correspond to when the heart is beating.

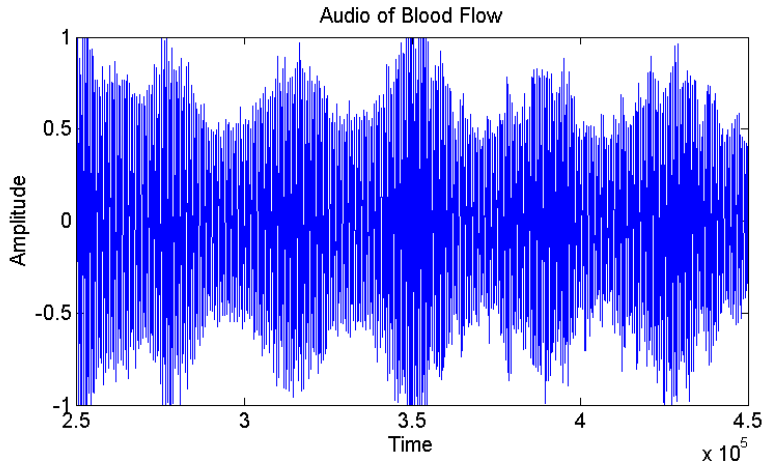

Figure 12. Audio signal of heart blood flow

A spectrogram was obtained from the signals. The spectrogram window length was varied. Narrow and wide window lengths were programmed. Figures 13-14 show the results of this windowing respectively. The narrow length gave more detail. A lot of velocity profile details

were lost due to the wide window length. The narrow window length had a higher resolution, and was chosen for all the spectrograms generated.

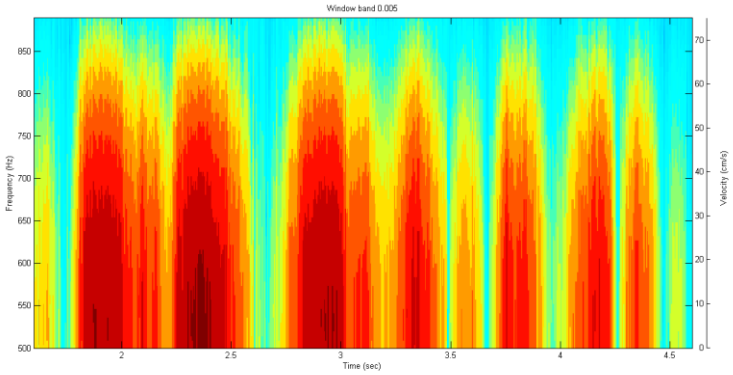

Figure 13. Narrow window length for spectrogram

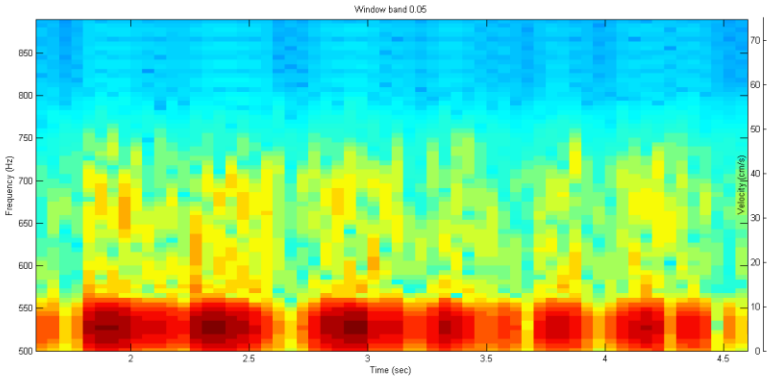

Figure 14. Wide window length for spectrogram

Spectrograms helped analyze the signal, seen in Figure 15. There is a lot of high frequency noise, and the Doppler shift frequency is relatively low. Low-pass filters were chosen to filter the signal.

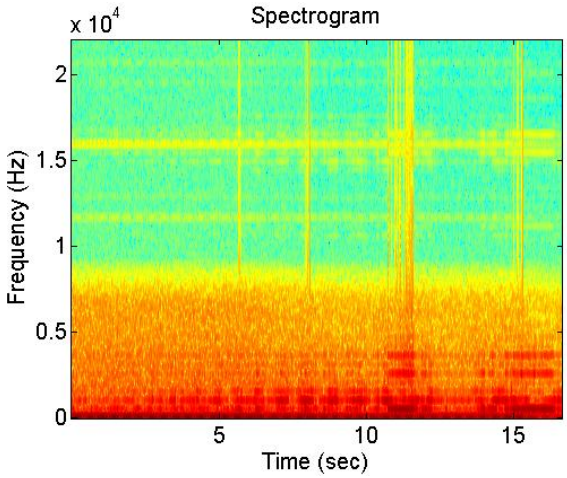

Figure 15. Spectrogram of signal

Several low-pass filters were designed. Two digital filters were tested. Figure 16 shows the result of an infinite impulse response filter (IIR), and Figure 17 shows the result of a finite impulse response filter (FIR). The IIR filter had more noise. The FIR filter has better stability, but has a higher order. The FIR filter was chosen becasue the signal quality was better.

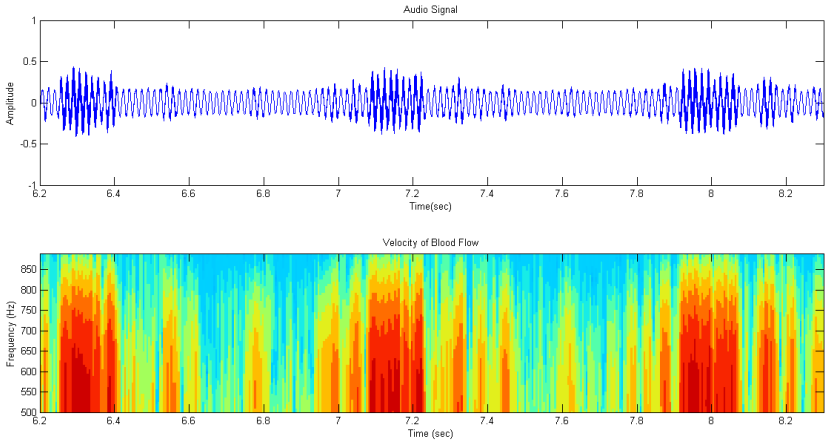

Figure 16. IIR filter results

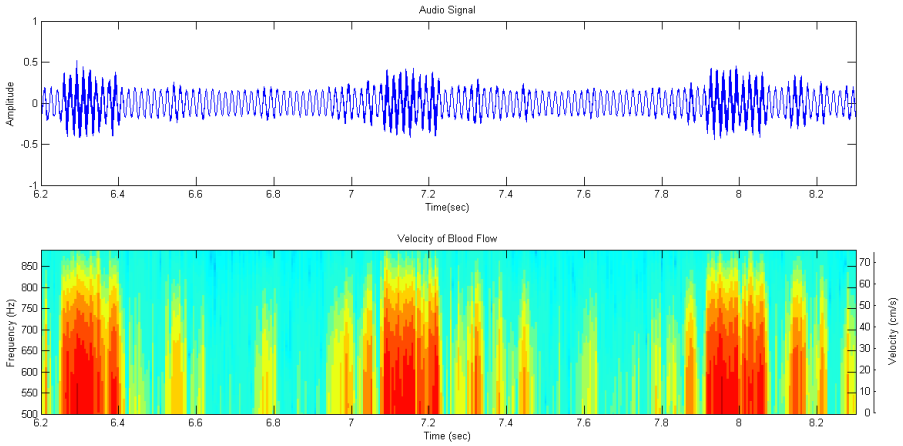

Figure 17. FIR filter results

Different cut off frequencies were tested. One low-pass filter had an 800 Hz cut off frequency, and another had a 700 Hz cut off frequency. The velocity was calculated using Equation 3. The velocity is displayed on the right hand y-axis. Figures 18-19 show the two filtered signals.

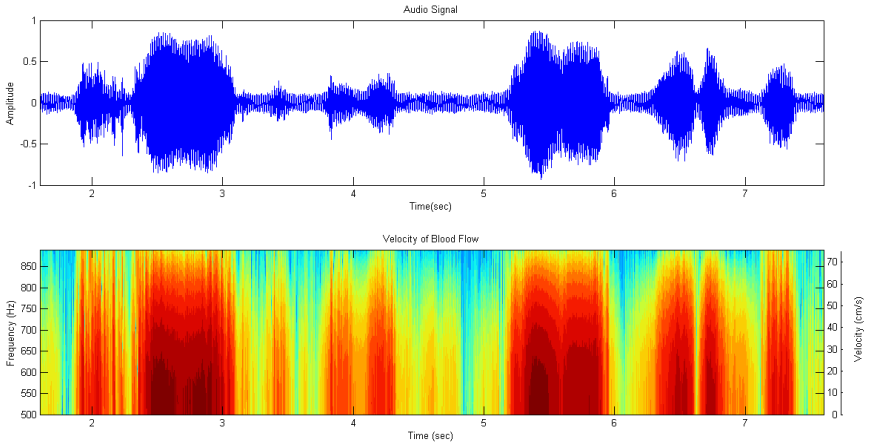

Figure 18. Filtered audio signal with 800 Hz cut off

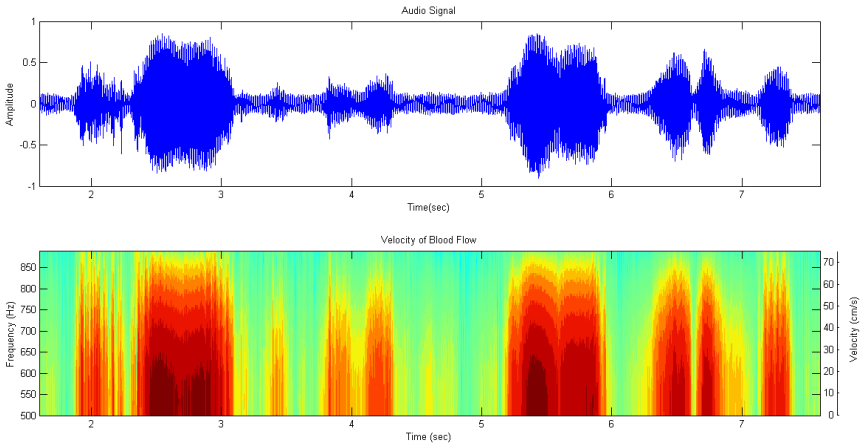

Figure 19. Filtered audio signal with 700 Hz cut off

The low-pass filter with a cut off frequency at 700 Hz was selected to analyze signals because it better divided the shades between colors and filtered more noise between the heart beats. Figures 20-21 show two audio signals from different subjects filtered with the 700 Hz low pass-filter.

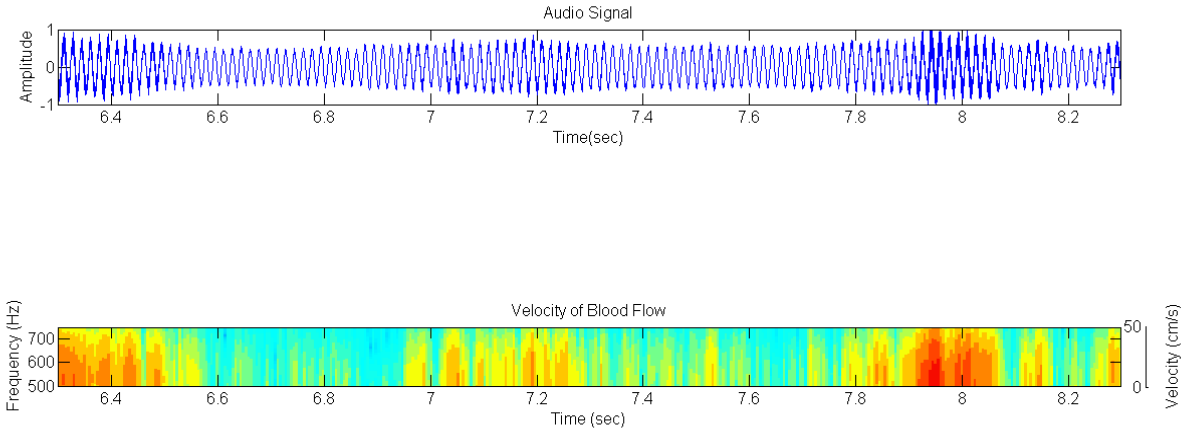

Figure 20. Heart rate signal from subject 1 and spectrogram

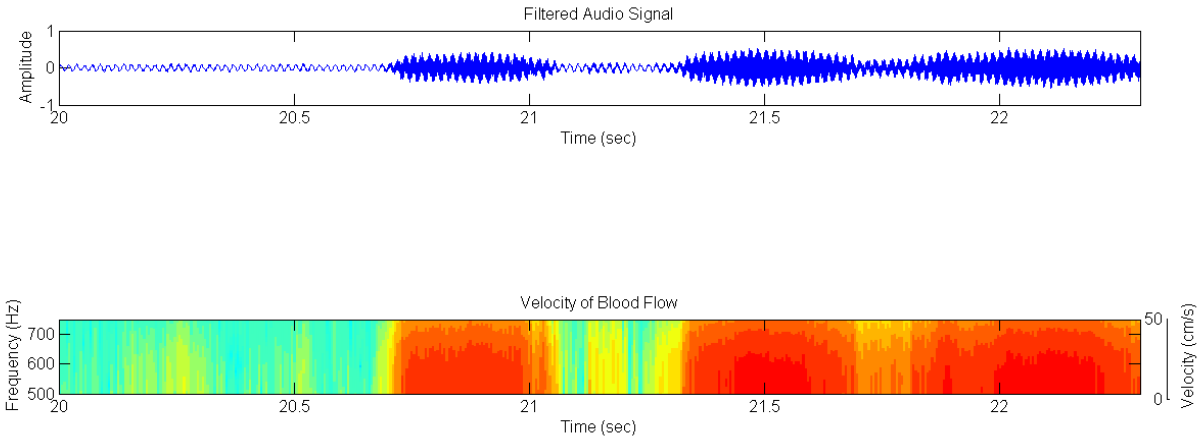

Figure 21. Heart rate signal from subject 2 and spectrogram

A final test was done to test the signal processing method. The resting and recovery heart rate was recorded for a subject. Both of these signals were processed, and the results are shown in Figure 22-23. The resting heart rate shows a regular beat with similar trends to the other recorded signals. The recovery heart rate shows a different velocity profile. The heart is beating faster and pumping more blood, observed from the increase in the red color on the spectrogram. This result showed the signal processing method is capable of processing signals from the heart under different conditions.

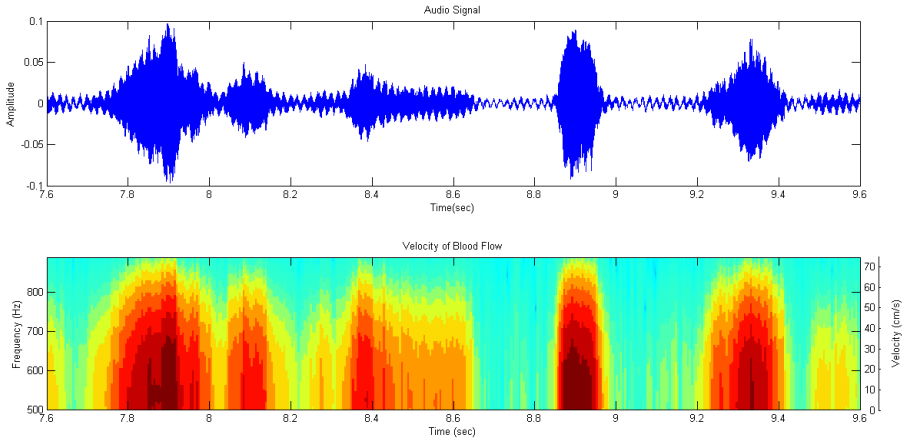

Figure 22. Resting heart rate

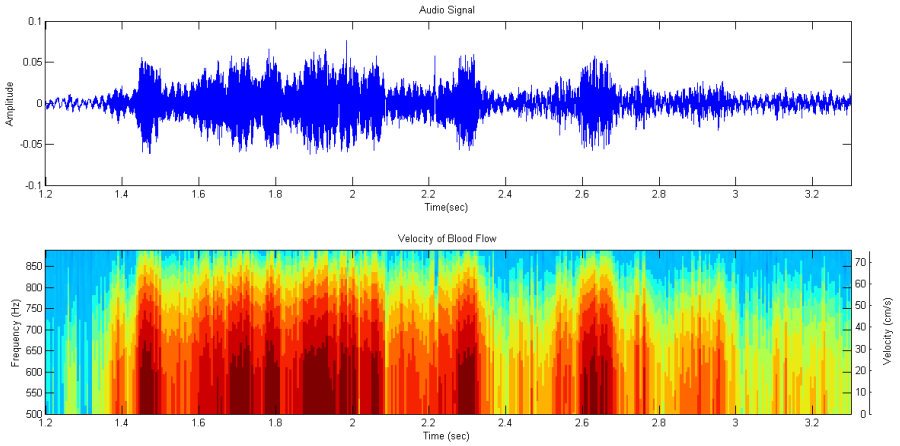

Figure 23. Recovery heart rate

The spectrograms show a roughly parabolic trend over time, similar to the ones seen in Figure 5. The spectrograms show how velocity changes with time. The most concentrated parts are shown in red and correlate to a velocity around 30 cm/s. The spectrograms show that heart beats correlate to an increase in magnitude in the time domain.

VI. CONCLUSIONS

MATLAB was used for signal processing of an ultrasonic blood flow audio signal. A design for the processing method was determined after tests. An acceptable low-pass filter was applied to the signals. The spectrogram plots were able to display blood velocity profiles. A roughly parabolic shape was observed as well as an increase in magnitude to the audio signal when the flow increased (Figures 18-19). Future work is necessary. Another testing experiment should be conducted to ensure accuracy. The current velocity profiles seem correct based on other research, but an actual test would be beneficial. A final recommendation is to attempt real-time signal processing.

VII. ACKNOWLEDGEMENTS

We wish to thank the Northern Illinois University Department of Electrical Engineering for funding and support for this project.

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