Project #4

Acoustic Properties Measurement of a Medium Using an Ultrasound System

BE 5344

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Introduction

Ultrasound technology is an important tool that is used for medical and industrial imaging. In medicine, ultrasound is a crucial tool used for life-saving emergencies and clinical examinations. During cardiopulmonary resuscitation, Emergency physicians will perform a Focused Cardiac Ultrasound (FOCUS) to check the activity of the heart and determine if ACLS should be continued. [1,3] They also use ultrasounds to evaluate other medical emergencies: eye ultrasounds look for retinal detachments, pelvic ultrasounds check for ectopic pregnancies, and venous ultrasounds look for DVT (Deep Venous Thrombosis). [3,5] In the clinical setting, the staple ultrasound examination is the fetal ultrasound. Early on, physicians will use it to determine the location of the pregnancy. Later, an ultrasound will be used to evaluate the status of the fetus's development during pregnancy. [3]

Ultrasounds can produce images due to acoustic waves and the acoustic impedance of tissues. The ultrasound transducer is made of a plate of piezoelectric material within two thin metal electrodes on each face. Currently, lead zirconate titanate ceramic composites are used as piezoelectric material. [4] A current is applied to the crystals, causing them to vibrate. This vibration produces a high-frequency acoustic wave that is emitted. The wave will travel and hit a tissue, object, etc. Depending on the material's acoustic impedance, a portion of the energy will be absorbed, and the rest will be reflected. The wave then travels back to the transducer, causing the crystals to vibrate again. The vibrations are converted into an electrical current and that signal is acquired. [2] Filtering and signal processing is performed, and an image is displayed.

In this project, we will be using an ultrasound transducer to visualize silicone tubes in A-mode. We will be comparing the differences in the signal of a silicone tube filled with air and one with water.

Methods

The project involved setting up the parts to be able to obtain data provided by the single element transducer. The following components were utilized to construct the setup needed for the project:

- 1 MHz single element, focused transducer
- Translation and rotation stages
- Optical breadboard
- Two silicone hollow tubes within transparent silicone phantom
- Syringe
- Digital Storage Oscilloscope
- Container with water
- Olympus 5073PR Pulser/Receiver
- Wires for oscilloscope
- Wires for pulse and receiver device

Below is the representation of the setup and components that were utilized:

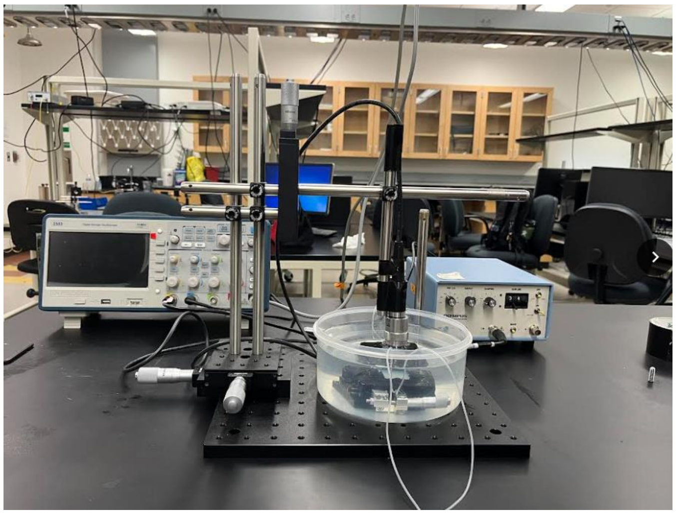

Figure 1. Project setup.

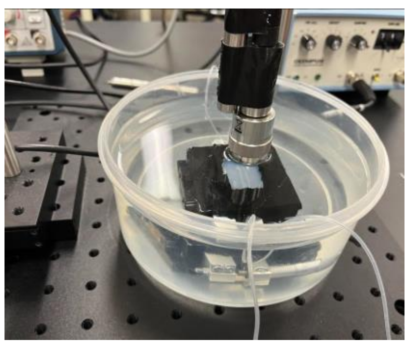

Figure 2. Setup of the transducer in the container with water.

(a) (b)

Figure 3. (a) Oscilloscope and (b) pulse and receiver devices used.

Figure 4. 1 MHz focused transducer.

The setup included building an optical breadboard with three translation and rotation stages and a transducer. Next, a container with the water and silicone phantom with two tubes placed inside the container. The container was next placed on the optical breadboard. The next step included positioning the 1 MHz single element, focused transducer 1 inch away from the surface of the silicone phantom by utilizing translation and rotation stages. Three translation and rotation stages were utilized to control x, y, and z positioning of the transducer. The silicone phantom immersed in water included two hollow silicone tubes with an inner diameter of 0.030 inch and an outer diameter of 0.065 inch. These tubes were used to obtain data with conditions when they were filled with air and water.

The pulse and receiver device's PRF was set to 500 Hz, Energy to 4, Damping to 2, and the gain in dB was set to 34. The pulse and receiver device were connected to the 1 MHz transducer. When turned on, the pulse and receiver device sent electrical signal to the transducer and the transducer produced an ultrasound wave which interacted with the silicone tubes. The ultrasound wave bounced back from the silicone tube's walls back to transducer. The tube has 4 boundaries that should create a waveform like signal with 4 peaks when ultrasound signal bounces from the following boundaries: 1) the water/outer surface, 2) inner surface/air or water, 3) air or water/inner surface and 4) water/outer surface (Figure 5). The obtained ultrasound wave signal is converted into an electrical signal with the help of transducer and the electrical signal is sent to the pulse and receiver device.

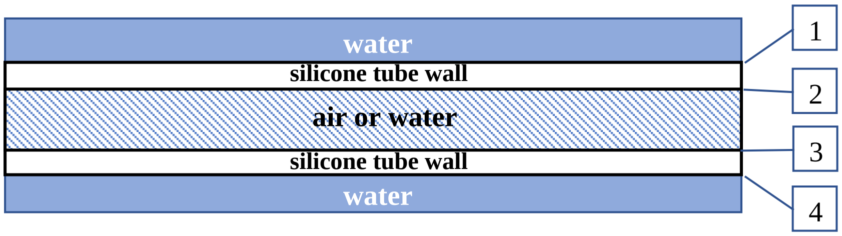

Figure 5. Representation of the silicone tube's four boundaries reflecting the ultrasound signal.

Important steps included removing bubbles from the surface of curved focused transducer when transducer was submerged in water. To focus the transducer on the tubes, three translation and rotation stages were adjusted to obtain maximized signal on the oscilloscope. Changing the position of the z axis translation and rotation stage resulted in horizontal changes on the oscilloscope. Changing the position of the x axis translation and rotation stage resulted in attenuation or amplification of the signal. The main goal was to place the transducer right in the middle of the tube.

The pulse and receiver device also sent concurrent signal to oscilloscope when it sent the signal to the transducer and the sent signal is called the trigger signal. Next, upon receiving the resulting electrical signal from the transducer, the pulse and receiver device sent the signal to oscilloscope which graphed the obtained signal and represented on its screen in the form of a wave. Oscilloscope had the screen's division set to 5 V vertically and 50 µs horizontally. The triggering signal from the pulse and receiver device vertically matched the reference line on the oscilloscope. The signal in the form of the wave that came after the triggering signal was the desired signal to be recorded. The desired signal was recorded on the flash drive to be processed later.

Results and Discussion

The data recorded from the oscilloscope in .csv files were first plotted in MATLAB for both experiments, where air and water were injected into the silicone tubes (Figures 6 and 7).

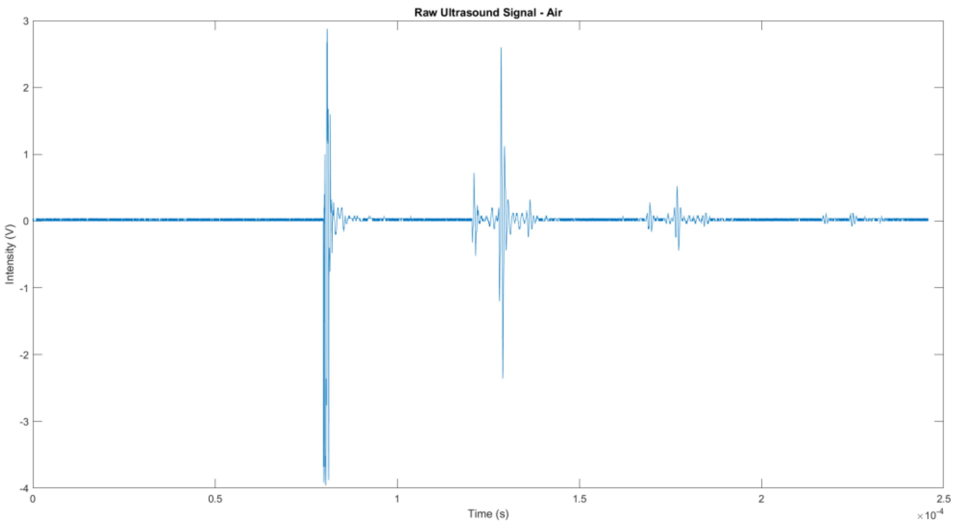

Figure 6. Raw ultrasound signal reflected from the silicone phantom containing silicone tubes injected with air.

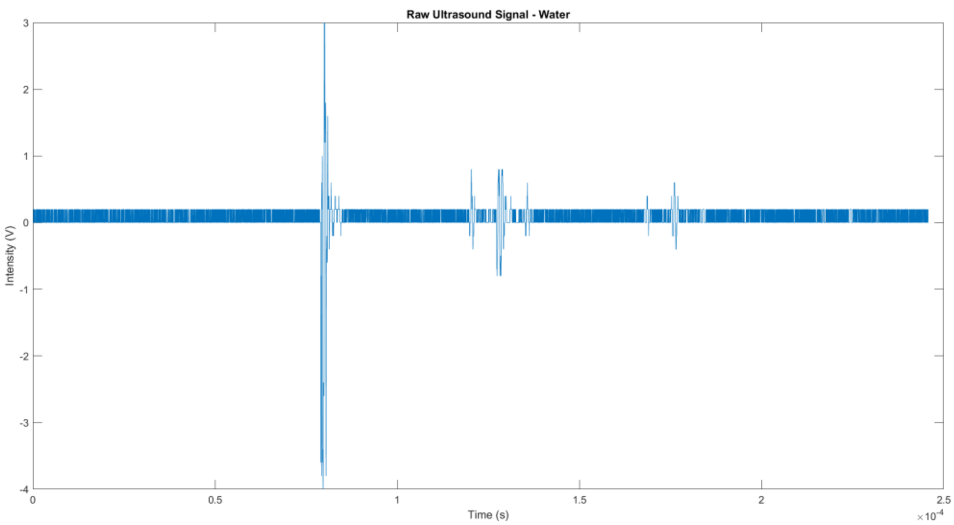

Figure 7. Raw ultrasound signal reflected from the silicone phantom containing silicone tubes injected with water.

FFT was performed in MATLAB to determine the optimal filter to remove the high-frequency noise from each acquired signal (see code in Appendix). A lowpass filter with a cutoff frequency of 190kHz was applied to the signal from the first experiment with air (Figure 8).

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Meanwhile, a bandpass filter with cutoff frequencies of 1MHz and 1.9MHz was applied to the signal from the second experiment with water (Figure 9). From Figures 8 and 9, we observed that the reflection signal from the silicone tube was received about 40µs after the pulse signal was triggered. This result matches the predicted travel time (τ) calculated by the formula $r = \frac{v*\tau}{2}$, where r =1 inch (distance between the transducer and the object) and v = 1540 m/s (velocity of sound in water).

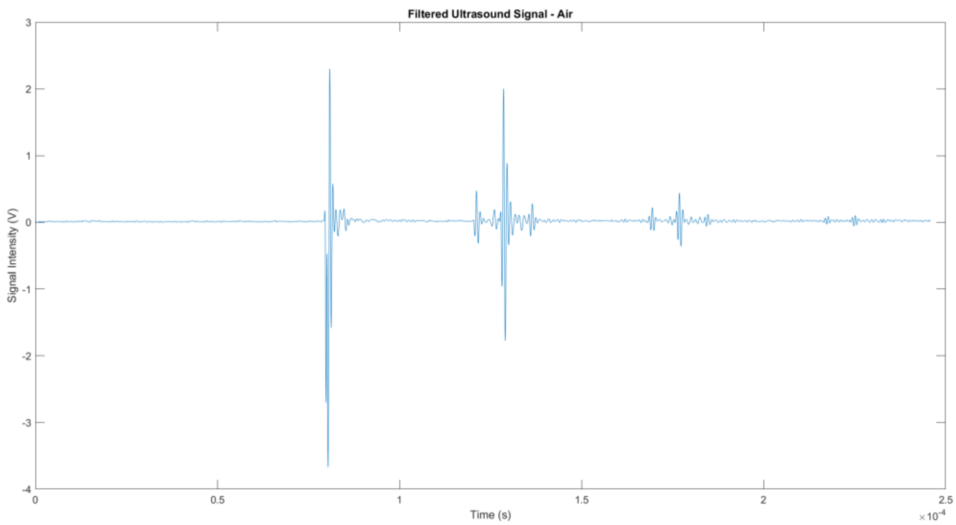

Figure 8. Ultrasound signal reflected from the silicone tube injected with air after lowpass filtering.

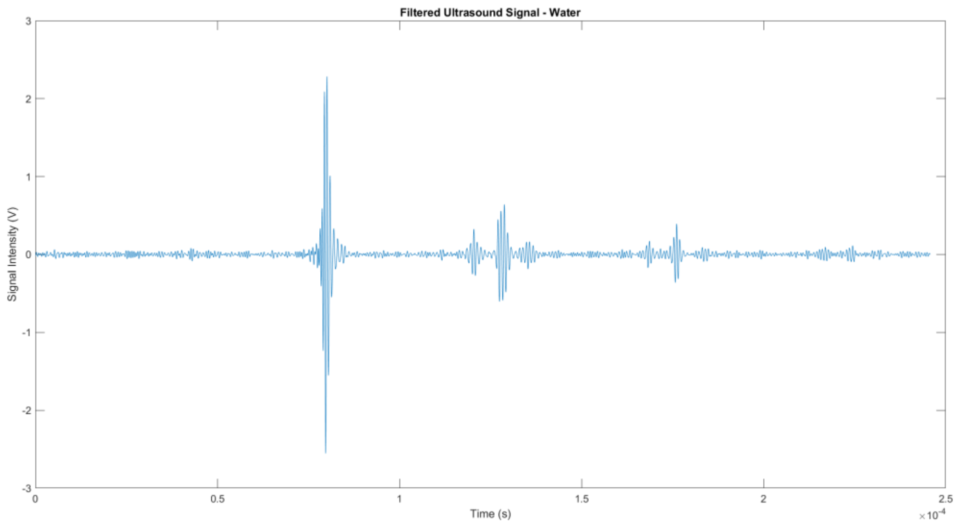

Figure 9. Ultrasound signal reflected from the silicone tube injected with water after bandpass filtering.

The reflection of the ultrasound signal off the silicone tube's different boundaries is represented by the waveform at the center of each signal. The MATLAB function 'envelope' was used to generate peak envelopes from the signal to help distinguish between these boundaries (see code in Appendix). Focusing in on this central waveform, we saw the expected four peaks representing the four different boundaries in the ultrasound signal reflected from the silicone tube injected with air (Figure 10). However, in Figure 11, we missed one peak when we were expecting two larger peaks representing the two boundaries separating the inner walls of the tube and the injected water. This may be because the inner diameter of the tube is small, so the distance between the two boundaries translates into a very minimal distance between their representative peaks, causing them to be encompassed within a single large envelope. Meanwhile, the two smaller peak envelopes on either side represent the boundaries between the outer surfaces of the silicone tube and the water in which it was submerged.

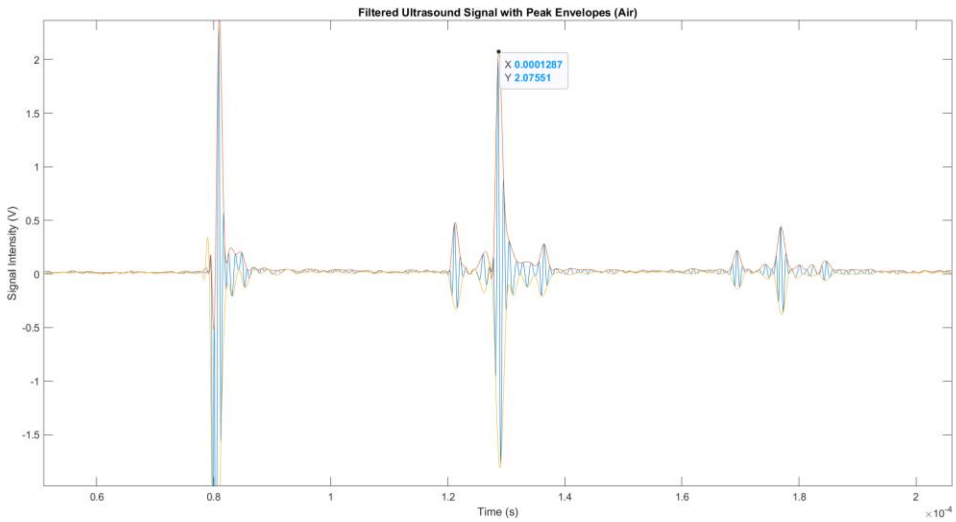

Figure 10. Peak envelopes of ultrasound signal reflected from the silicone tube injected with air.

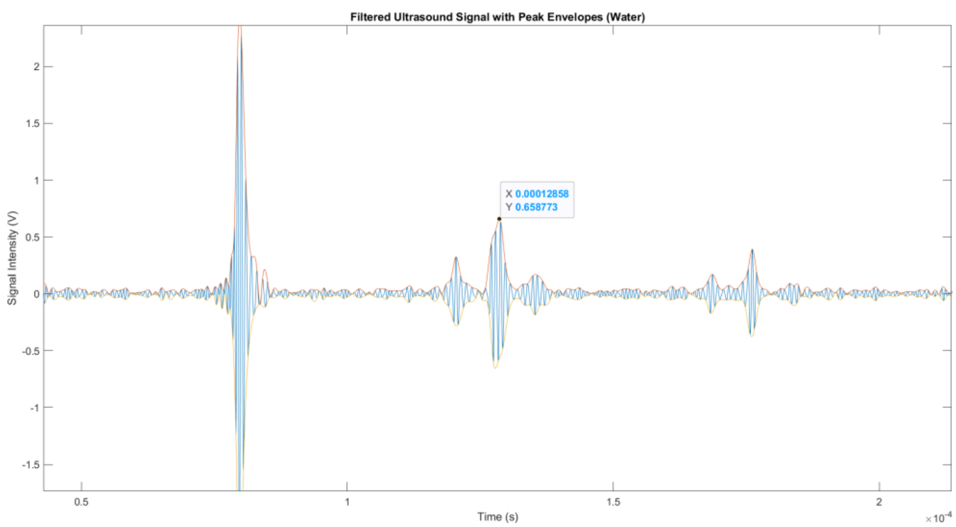

Figure 11. Peak envelopes of ultrasound signal reflected from the silicone tube injected with water.

The intensity of the signal reflected at the boundary between two media depends on the difference between the acoustic impedances of the two media. This relationship is modeled by the equation for calculating the pressure amplitude reflection coefficient R_{amp}, where Z_1 and Z_2 are the acoustic impedances of the two media of interest. The following form of the equation can be used since the ultrasound transducer was placed directly above and orthogonal to the silicone tube, so the angles of incidence, reflection, and transmission should all equal 0^{o}. The greater the difference between the two acoustic impedances, the greater the reflection coefficient will be. This means that a higher percentage of acoustic energy will be reflected and received by the transducer, resulting in a stronger signal.

$$R_{amp} = \frac{Z_2 - Z_1}{Z_2 + Z_1}$$

Air has an acoustic impedance of 429 kg/m^2s, while water has a much higher acoustic impedance of 1.5×10^{6} kg/m^2s [6]. According to one study, silicone rubber has a similarly high acoustic impedance of 1.0×10^{6} kg/m^2s [7]. Thus, the difference between the acoustic impedances of air and silicone should be much higher than that between water and silicone. Our results corroborate this as the reflected signal was stronger when air was injected into the silicone tube. The largest peak envelope representing the boundary between the injected air and the tube's inner walls had a peak intensity of 2.08V (Figure 10). In contrast, this value decreased to 0.66V when water was injected into the silicone tube instead, so the signal became weaker (Figure 11).

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Commented [TN4]: (PDF) Low Sound Velocity and Acoustic Attenuation Silicone Rubber Lens Based on Nano-Powder-Composite for Medical Echo Ultrasound Array Probes (researchgate.net)

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Conclusion

In conclusion, four peaks representing four different boundaries reflecting the ultrasound signal were expected and present for the air measurements. However, only three were obtained for the water measurements. We suspect that this observation could be due to an error in the experimental set-up, the time taken to record the signals, or the equipment used to measure the signal. Despite this, attenuation of the ultrasound wave was observed as expected during the measurement of the silicone tube filled with water. In comparing the results of the silicone tube with air and water, we saw that the amplitude of the silicone tube filled with air was higher than that filled with water due to a greater difference in the acoustic impedances. For future experiments we recommend recording multiple sets of data to see if these results are repeatable, however, as we were limited in time, we were unable to do so.

References

[1] Abdolrazaghnejad, A, Banaie, M, Safdari, M. (2018). Ultrasonography in Emergency Department; a Diagnostic Tool for Better Examination and Decision-Making. *Advanced Journal of Emergency Medicine, Winter 2(1)*

[2] ECG and Echo Learning. The Ultrasound Transducer. *Clinical Echocardiography*. https://ecgwaves.com/topic/the-ultrasound-transmitter-probe/

[3] Galdamez, L. (2018). The Evolving Role of Ultrasound in Emergency Medicine. *Essentials of Accident and Emergency Medicine.*

[4] Iowa State University Center for Nondestructive Evaluation. Piezoelectric Transducers. Nondestructive Evaluation Techniques.
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[5] Needleman, L, Cronan, J, Lilly,M, Merli, G et al. (2018). Ultrasound for Lower Extremity Deep Venous Thrombosis. *Circulation, 137(14),* 1505-1515.

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[7] Yamashita, Y, Hosono, Y, Itsumi, K. (2007). Low Sound Velocity and Acoustic Attenuation

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Appendix

Matlab Code

```
clear
close all
clc

%% Air Injected in Silicone Tubes
%Import data and plot signal
Air = readmatrix('BK000001.csv');
A = Air(:,2); %extracting only data from CH1
L = length(A);
fs = 50000000; %sampling frequency (Hz)
T=1/fs; %period (s)
t = (0:L-1)*T; %time vector
figure
plot(t,A)
xlabel('Time (s)')
ylabel('Intensity (V)')
title('Raw Ultrasound Signal - Air')

%Generate frequency spectrum using FFT
fs = 50000000; %sampling frequency (Hz)
L = length(A);
y = fft(A);
ds = abs(y/L); %double-sided amplitude spectrum
ss = ds(1:(L/2)+1);
ss(2:end-1) = 2*ss(2:end-1); %single-sided amplitude spectrum
f = (0:L/2)*fs/L; %converts freq axis from freq bins to Hz
figure
plot(f,ss)
xlabel('Frequency (Hz)')
ylabel('Amplitude')
title('Single-Sided Amplitude Spectrum')

%Filter the signal
T=1/fs;
t = (0:L-1)*T;
y1 = lowpass(A,190000,fs);
[up,lo] = envelope(y1,5,'peak');
figure
plot(t,y1,t,up,t,lo)
hold on
title('Ultrasound Signal with Peak Envelopes (Air) after Filtered')
xlabel('Time(s)'),ylabel('Signal Intensity (V)')
hold off

%% Water Injected in Silicone Tubes
%Import data and plot signal
Water = readmatrix('BK000002.csv');
W = Water(:,2);
```

```
figure
plot(W)
xlabel('Sample Number')
ylabel('Intensity (V)')
title('Raw Ultrasound Signal - Water')

%Generate frequency spectrum using FFT
fs = 50000000; %sampling frequency (Hz)
L = length(W);
y = fft(W);
ds = abs(y/L); %double-sided amplitude spectrum
ss = ds(1:(L/2)+1);
ss(2:end-1) = 2*ss(2:end-1); %single-sided amplitude spectrum
f = (0:L/2)*fs/L; %converts freq axis from freq bins to Hz
figure
plot(f,ss)
xlabel('Frequency (Hz)')
ylabel('Amplitude')
title('Single-Sided Amplitude Spectrum')

%Filter the signal
T=1/fs;
t = (0:L-1)*T;
y1 = bandpass(W,[1000000 1900000],fs);
[up,lo] = envelope(y1,5,'peak');
figure
plot(t,y1,t,up,t,lo)
title('Ultrasound Signal with Peak Envelopes (Water) after Filtered')
xlabel('Time(s)'),ylabel('Signal Intensity (V)')
hold off
```