Digital Signal Processing | Final Project

Robert Thomas
Department of Electrical and Computer Engineering
University of North Carolina at Charlotte
Charlotte, NC, USA
rthoma97@charlotte.edu

CONTENTS

I. INTRODUCTION

A. Background Information

Ultrasound imaging is a key diagnostic tool in medicine due to its non-invasive nature, affordability, and the fact that it doesn't involve radiation like X-rays or CT scans. It's widely used for monitoring pregnancies, examining internal organs, and guiding procedures like biopsies. However, one common issue with ultrasound images is the presence of *speckle noise*, which can make it difficult to interpret the images accurately.

Speckle noise is a granular pattern that appears in ultrasound images. It's a type of multiplicative noise that forms due to the interference of scattered sound waves from various tissue structures. The interference creates random variations in the image intensity, which can obscure important features such as tissue boundaries and internal structures. This makes it harder to obtain clear, diagnostic images, and is especially problematic in clinical settings where precision is critical.

To address this issue, de-speckling filters are often used to reduce the speckle noise. These filters aim to smooth out the granular pattern caused by the speckle without sacrificing the important diagnostic information contained in the image. The goal is to enhance the clarity of the image while preserving the anatomical details that are critical for accurate diagnosis.

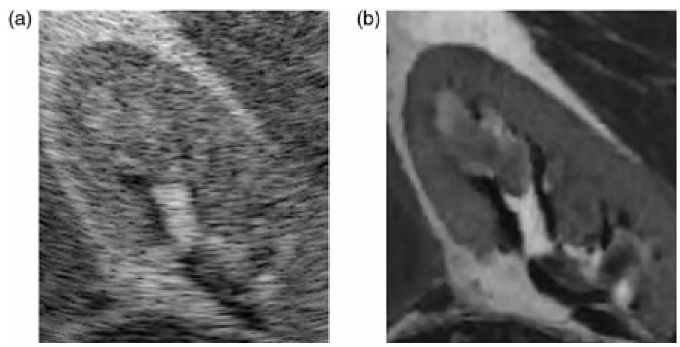


Fig. 1. Speckled Signal vs. Despeckled Signal [1]

An Infinite Impulse Response filter (IIR) is a filter that, once excited, may have an output for an infinite period of time. Two kinds of IIRs that are particularly useful in ultrasonic imaging: *Butterworth filters* and *Chebychev filters*.

A Butterworth filter will provide a smooth filtering for the gain, so all the frequencies within the bandpass output at the same gain, but will cut the frequencies on the edges at a steeper rate. A Chebychev filter will have a smoother cutoff but it have some ripple in the gain, meaning some frequencies will have more gain than others. This is shown in figure 2.

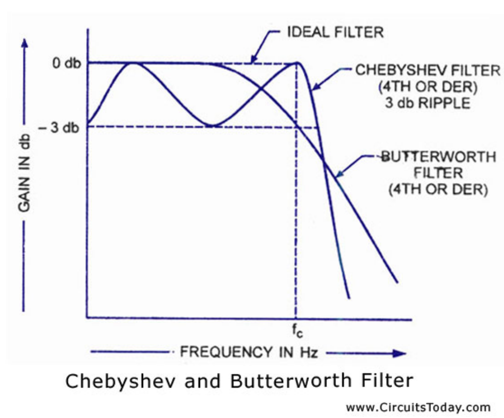


Fig. 2. Chebyshev filter and butterworth filter frequency response [2]

B. Project Overview

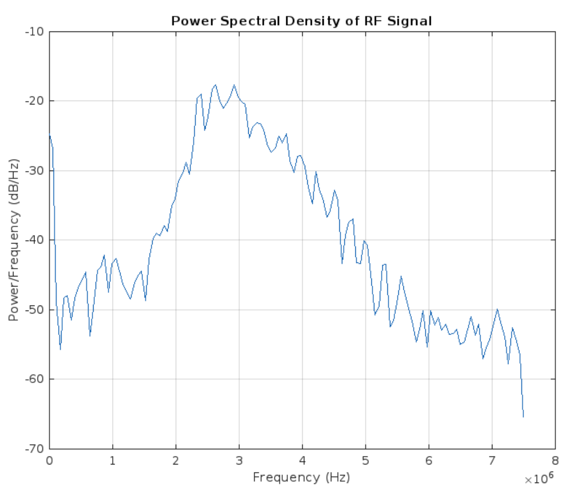
1) Task 1: Design the filters: For the Butterworth filter, plot the magnitude spectrum, phase spectrum, group delay, phase delay, pole zero plot from the Filter Designer App. Repeat the first step for a Chebychev type I filter.

2) Task 2: Apply the filters on Ultrasound RF Signals: Apply the filters to the ultrasound RF signal. To apply the (SOS,G) form of your filter, use the MATLAB command y = filtfilt(SOS,G,x). Plot the power spectrum using pwelch function for the filtered signals (select only one scanline). Show the ultrasound B-mode images for (i) no filter, (ii) Butterworth filter, (iii) Chebychev type I filter. Comment on the quality of the B-mode images after filtering. Quantitatively measure the effect of filtering using the measure speckle suppression index (SSI). For this, select two homogeneous regions (one at the top from the uterine muscle and another at the bottom from the placenta) within the B-mode image using the following commands: h = imrect; position = wait(h); I = imcrop(RF,position);

II. Procedure and Results

A. Task 1: Designing the Filters

1) Parameters: From the power spectral density of RF Signal II-A1, we can see that the frequencies with -40dB to -30dB of volume are found almost completely between 2MHz and 5MHz.



Therefore we will designate our cutoff frequencies as shown in Table I.

TABLE I
FILTER PARAMETERS

Parameter	**Frequency** (MHz)
Fstop1	1.9
Fpass1	2.1
Fpass2	4
Fstop2	4.5

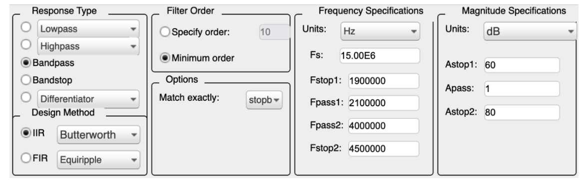


Fig. 3. Butterworth Filter Parameters

2) Butterworth Filter: Using the frequencies in table I, we can design our filter using the *filterDesigner* command in Matlab. We will set up the filter as shown in figure 3.

Using these specifications we get the plots in table II:

Three things are notable about this filter when examining the plots:

1) The magnitude response suggests the filter has a sharp cutoff for frequencies, which is useful for separating signals in different frequency bands.
2) The phase response and group delay show that the filter introduces phase distortion, especially near the cutoff, which is expected for certain filter designs.
3) The pole-zero plot reveals the filter's stability and gives insight into how the filter modifies the signal at different frequencies.

3) Chebychev Filter: Using the frequencies in table I, we can design our filter using the *filterDesigner* command in Matlab. We will set up the filter the same as the Butterworth filter as shown in figure 3 except we will select *Chebychev I* from the *Design Method* panel. Using these specifications we can achieve the filter plots in table III.

A few notable observations from these plots:

1) The Chebyshev Type I filter exhibits a sharp cutoff and a steep roll-off, especially in the magnitude response. This is typical of Chebyshev filters, which are designed to minimize the ripple in the passband while providing a steep transition to the stopband.
2) Phase distortion is introduced in the transition region, as seen in the phase response and group delay plots. Chebyshev Type I filters are known for their non-linear phase response, which leads to phase shifts, especially near the cutoff frequency.
3) The group delay spikes indicate that the filter causes frequency-dependent delays in the transition region. This is a characteristic of filters with a sharp roll-off like the Chebyshev Type I, which may lead to time-domain distortions around the cutoff frequency.
4) The phase delay is relatively constant in the passband but increases sharply near the cutoff frequency, highlighting the phase distortion that occurs with a Chebyshev filter.
5) The pole-zero plot confirms the filter's stability. The poles are placed on the left half-plane of the complex plane, indicating that the filter is stable, with the distribution of poles contributing to the sharp roll-off behavior in the frequency response.

B. Task 2: Applying the filters on Ultrasound RF Signals

TABLE II
BUTTERWORTH FILTER

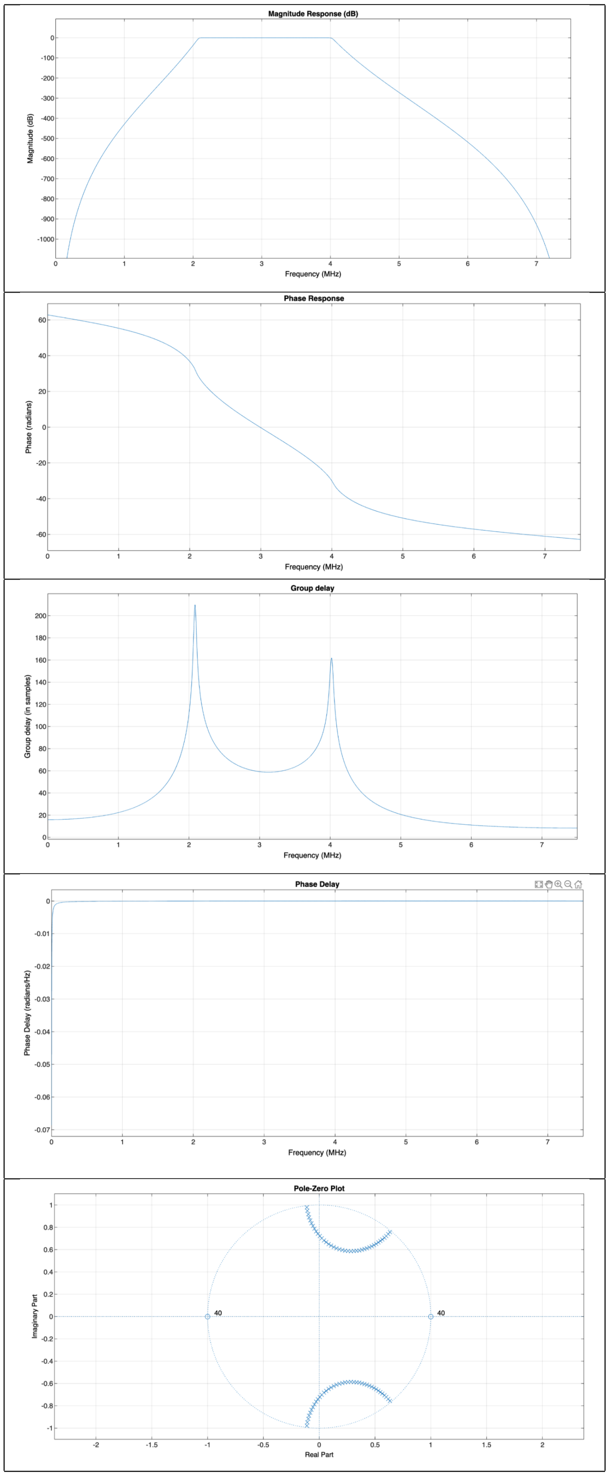
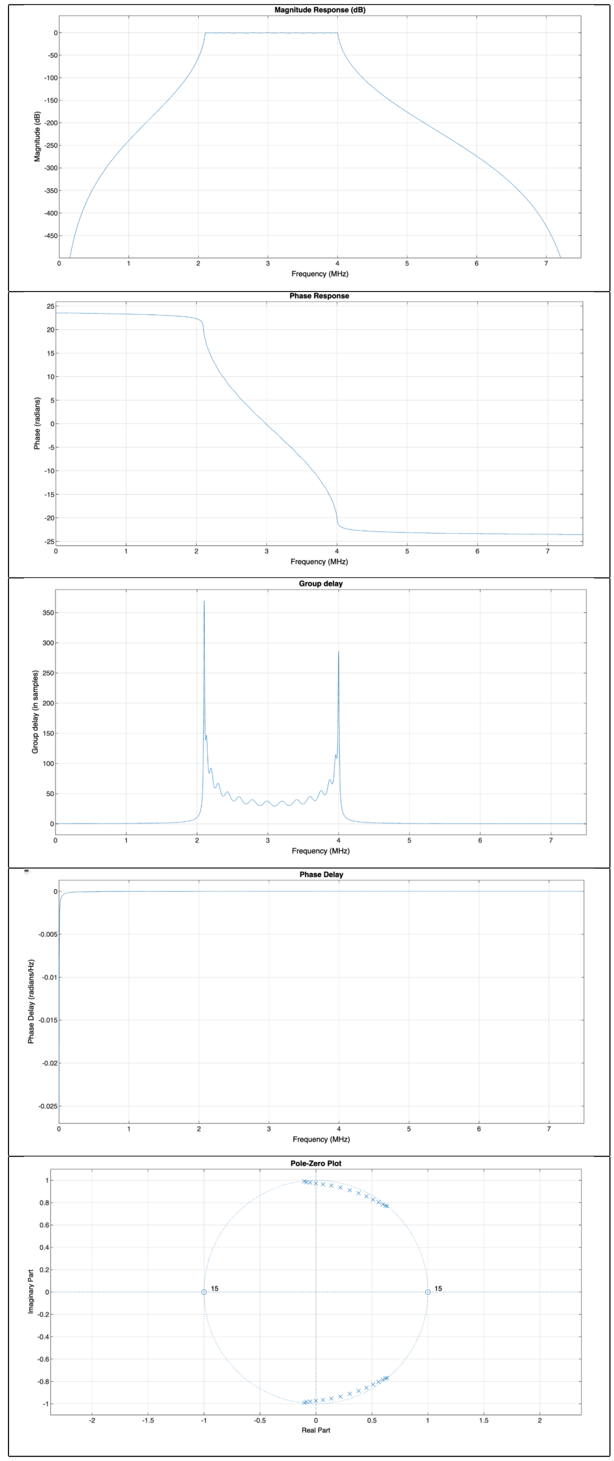


TABLE III
CHEBYCHEV FILTER



1) Power Spectrums: The plots in figure 4 show the power spectrum of a signal before and after applying two different types of filters: a Butterworth filter and a Chebyshev filter. The power spectrum represents the distribution of power across different frequencies in the signal. The top plot displays the spectrum of the original (unfiltered) signal, the middle one shows the spectrum after applying the Butterworth filter, and the bottom one shows the spectrum after applying the Chebyshev filter.

In the original signal (top plot of figure 4), the power is distributed across a wide frequency range, with significant

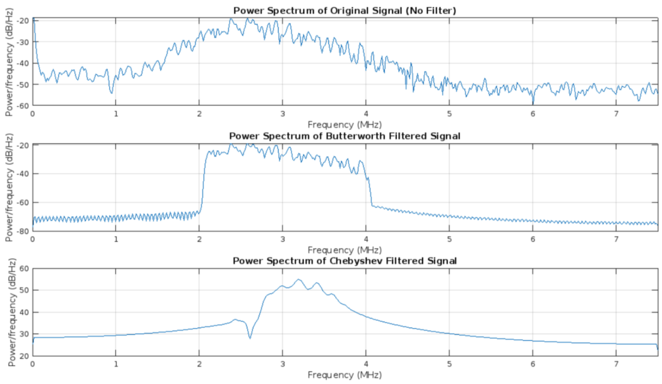


Fig. 4. Power Spectrum of Filtered Signals

energy in higher frequencies. The Butterworth filter (middle plot) significantly attenuates higher frequencies, resulting in a much more pronounced low-pass filter behavior. The abrupt cutoff observed in the Butterworth filter's spectrum indicates that it has a smooth transition from passband to stopband with no ripple in the passband or stopband, which is a characteristic feature of the Butterworth filter. This is ideal when a smooth and consistent response is desired.

The Chebyshev filter (bottom plot of figure 4) has a different frequency response. While it also attenuates high frequencies, it introduces ripples in the passband, which can be observed in the plot. This is characteristic of a Chebyshev Type I filter, which sacrifices smoothness in the passband in exchange for a sharper transition between passband and stopband. The Chebyshev filter's frequency response shows a much steeper drop from the passband to the stopband compared to the Butterworth filter, which can be advantageous when a sharp cutoff is needed, but it may introduce unwanted ripple in the passband.

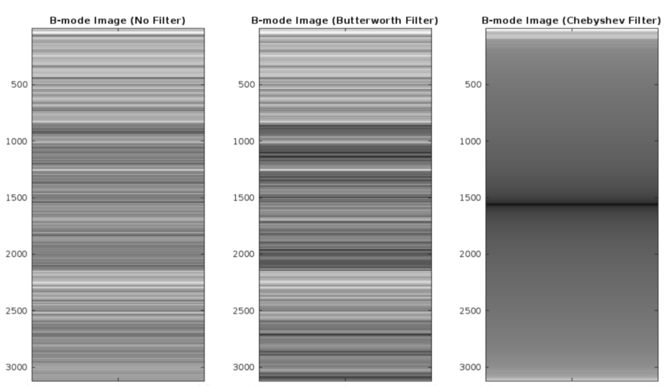


Fig. 5. B-Mode Images

2) B-Mode Images: B-mode (brightness mode) images are commonly used in ultrasound imaging to display the internal structure of tissues. These images are generated by plotting the amplitude of the backscattered ultrasound signals as brightness or intensity values, creating a grayscale image. The B-mode image essentially maps the variations in tissue density and the resulting changes in the acoustic impedance, which affect the way the ultrasound waves are reflected back to the transducer. Stronger reflections correspond to brighter areas, while weaker reflections produce darker areas.

The images shown in figure 5 depict the B-mode images of an ultrasound signal before and after applying different filters. The first image, labeled "B-mode Image (No Filter)," shows the original, unfiltered signal. You can observe the speckle noise in the image, which manifests as granular, high-frequency variations. This noise is typically caused by the scattering of sound waves by small tissue structures, such as cells or muscle fibers.

The second image, "B-mode Image (Butterworth Filter)," shows the result after applying a Butterworth filter. The Butterworth filter is a low-pass filter, meaning it attenuates higher frequencies while allowing lower frequencies to pass through. As a result, the image appears smoother, with a reduction in speckle noise. The smooth transition between the passband and stopband of this filter helps to retain the essential features of the image while reducing unwanted noise.

The third image, "B-mode Image (Chebyshev Filter)," shows the result of applying a Chebyshev Type I filter. This filter also reduces high-frequency noise but does so with ripples in the passband. The resulting image may exhibit sharper transitions between different tissue types, but it can also introduce some distortion or artifacts in the areas of interest. The Chebyshev filter's steeper cutoff makes it more aggressive in removing high-frequency components compared to the Butterworth filter. However, the ripple effect can make it less desirable in some medical imaging scenarios where uniformity is critical.

3) SSI Calculations: The Speckle Suppression Index (SSI) is a measure used to evaluate how well a filter reduces speckle noise in ultrasound images. Speckle noise, which appears as a grainy pattern, is caused by the interference of backscattered ultrasound waves and can make it harder to interpret important details in the image. SSI compares the variance and mean of a region of interest (ROI) in both the original and filtered images. A lower SSI means better noise suppression, as it indicates that the filter has reduced unwanted noise without removing valuable tissue information.

In this project, SSI helps assess the performance of different filters, such as Butterworth and Chebyshev, when applied to raw ultrasound RF data. By calculating and comparing the SSI values of the original, Butterworth-filtered, and Chebyshev-filtered images, the goal is to see how well these filters improve image quality by reducing speckle noise. This is important for ensuring clearer and more accurate ultrasound images for diagnostic purposes.

It can be calculated using equation II-B3.

When calculating SSI there are three possible outcomes:

1) $SSI > 1$: this is ideal as it means that the filtered image will have reduced speckle, with enhanced contrast between the features of interest (e.g., uterine muscle and placenta).
2) $SSI = 1$: the filter is too weak so noise is left unfiltered.

$$SSI = \frac{\frac{\sqrt{Varience(\hat{g})}}{Mean(\hat{g})}}{\frac{\sqrt{Varience(g)}}{Mean(g)}} \quad (1)$$

Fig. 6. SSI Equation

3) $SSI < 1$: the filtered image will be overly smooth, with reduced detail and contrast, which means the filter may have been too aggressive.

For some reason, when I calculated SSI in Matlab I kept getting an SSI of 1 for all filtered outputs. This is really bad as an SSI of 1 indicates that the filter isn't really doing anything meaningful to the data and the output is the same as if it was unfiltered. I recoded it and even tried different values for my filter parameters and still kept getting the same outcome. I am genuinely baffled by this as the B-Mode images in figure 5 clearly indicate a jarring distinction between the filtered and unfiltered signals.

```
SSI for Uterine Muscle (No Filter): 1
SSI for Uterine Muscle (Butterworth Filter): 1
SSI for Uterine Muscle (Chebyshev Filter): 1
SSI for Placenta (No Filter): 1
SSI for Placenta (Butterworth Filter): 1
SSI for Placenta (Chebyshev Filter): 1
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Fig. 7. SSI Values

III. Conclusions

Despite not getting clear SSI values, the B-Mode images in figure 5 lend valuable insight on which filter is better for the right circumstances.

- The Butterworth filter achieves a good balance by reducing noise while maintaining important image features. It provides a smooth transition and avoids the introduction of noticeable artifacts.
- The Chebyshev filter, while highly effective in noise reduction, might cause some loss of important detail or introduce undesirable artifacts due to its steeper roll-off and ripple behavior.
- The No Filter image highlights the severity of speckle noise, which makes it harder to interpret the image accurately for diagnostic purposes.

In summary, these B-mode images visually demonstrate the trade-off between noise reduction and image detail preservation, which is critical for diagnostic clarity. Despite the SSI values being unhelpful, we can still conclude that both filters improve the image quality by reducing noise, but the Chebyshev filter might overly smooth the image and compromise diagnostic information in certain areas.

References

[1] R. Rosa and F. Monteiro, "Performance analysis of speckle ultrasound image filtering," *Computer Methods in Biomechanics and Biomedical Engineering: Imaging Visualization*, vol. 4, pp. 1–9, 12 2014.

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[3] A. V. Oppenheim, R. W. Schafer, and J. R. Buck, *Discrete-time Signal Processing*, 3rd ed. Pearson, 2010.

[4] A. Au and M. Zwank, "Ultrasound physics and technical facts for the beginner," https://www.acep.org/sonoguide/basic/ultrasound-physics-and-technical-facts-for-the-beginner, 2020, accessed: May 10, 2025.