Ultrasound Speckle Reduction by Filtering

Raj Patel
Electrical and Computer Engineering Department
University of North Carolina at Charlotte
rpate239@charlotte.edu

***Abstract* – Ultrasound imaging is a cost-effective, non-invasive diagnostic technique, but it suffers from speckle noise, which degrades image quality. This project explores the application of Butterworth and Chebyshev Type I filters to reduce speckle noise and improve B-mode ultrasound images. MATLAB tools were used for filter design, implementation, and performance analysis. Results are evaluated using visual inspection and the Speckle Suppression Index (SSI).**

I. Introduction

Ultrasound imaging, a cost-effective and non-radiative diagnostic method, often suffers from speckle noise, which reduces image clarity. Digital filtering techniques can effectively reduce this noise while preserving critical details. This project applies Butterworth and Chebyshev Type I filters to improve ultrasound B-mode image quality.

II. Methodology

A. Data Acquisition and Processing

The raw ultrasound RF data was collected and processed using MATLAB. The envelope of the RF signal was computed using the Hilbert transform, and B-mode images were generated by applying logarithmic compression to enhance visual contrast.

B. Filter Design

The filters were developed using MATLAB's Filter Designer tool. Passband and stopband frequencies were determined based on the Welch Power Spectral Density (PSD) analysis. A Butterworth filter was selected for its smooth, flat passband response, while a Chebyshev Type I filter—featuring intentional passband ripples—was designed in second-order section (SOS) format for improved stability.

C. Application and Analysis

Filtering was performed using zero-phase digital filtering (filtfilt) to avoid phase distortion. After filtering, PSD assessments were carried out to evaluate frequency-domain changes. For quantitative assessment, two uniform regions (top and bottom) within the images were selected. The Speckle Suppression Index (SSI) was calculated to quantitatively measure the level of noise reduction achieved by each filter.

III. Task 1: Filter Design

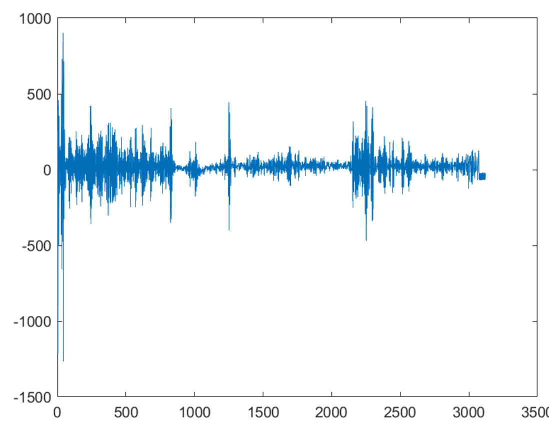

Figure 1: RF Data

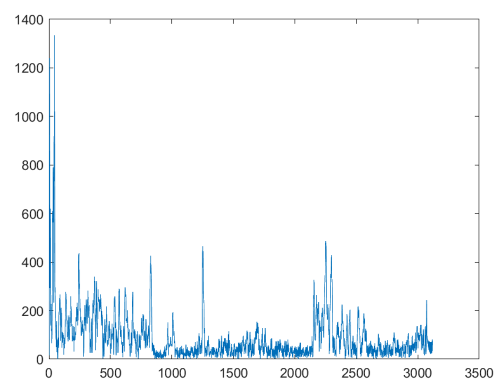

Figure 2: Envelope Data

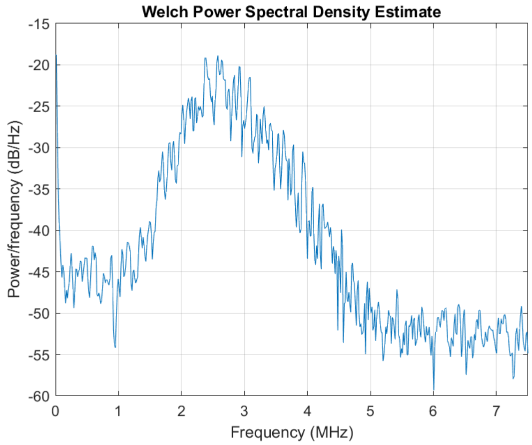

Figure 3: Welch Power Spectral Density Estimate

IV. Task 1: Butterworth Filter

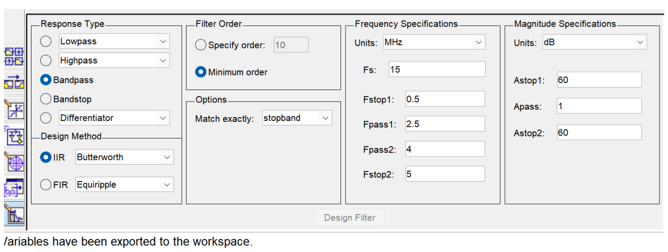

Figure 4: Butterworth Filter Parameters

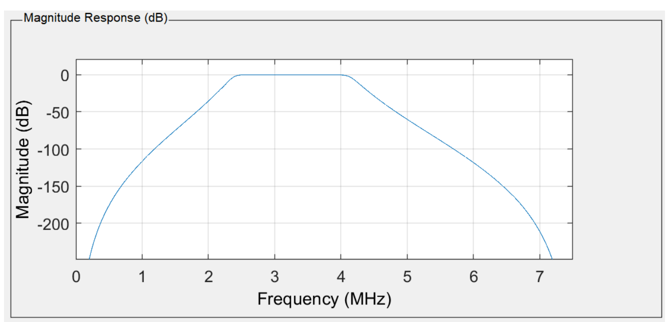

Figure 5: Butterworth Magnitude Spectrum

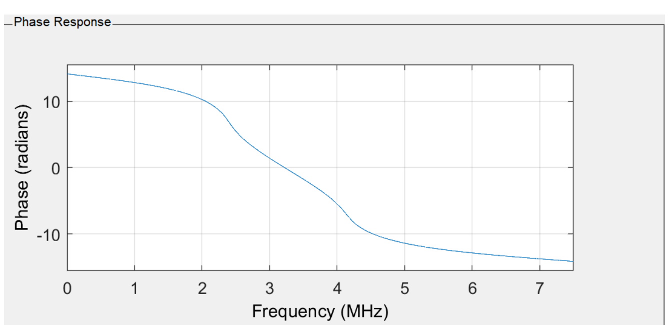

Figure 6: Butterworth Phase Spectrum

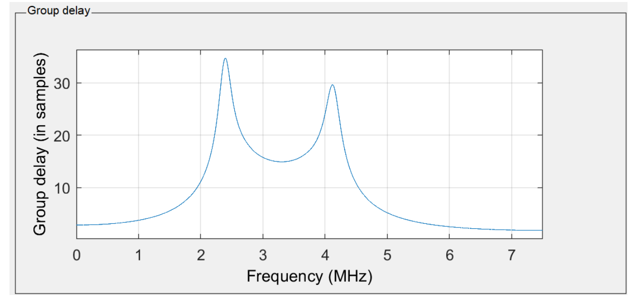

Figure 7: Butterworth Group Delay

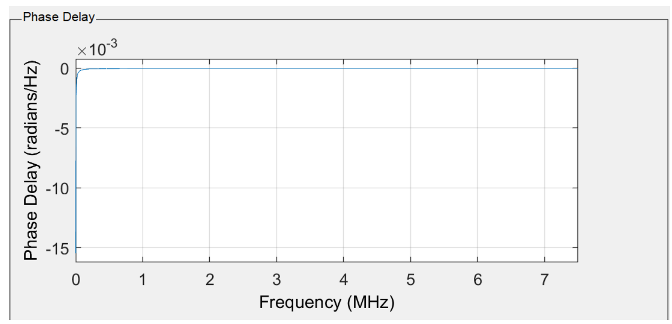

Figure 8: Butterworth Phase Delay

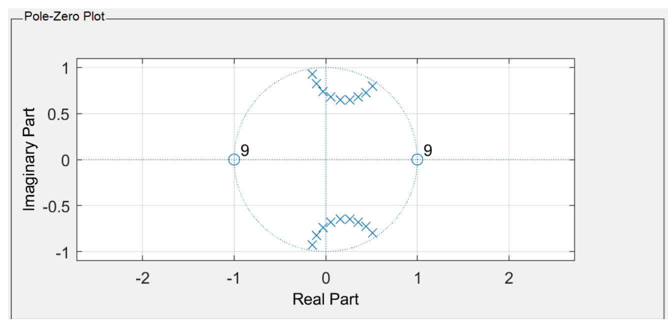

Figure 9: Butterworth Pole Zero Plot

V. Task One Chebyshev Type-1 Filter

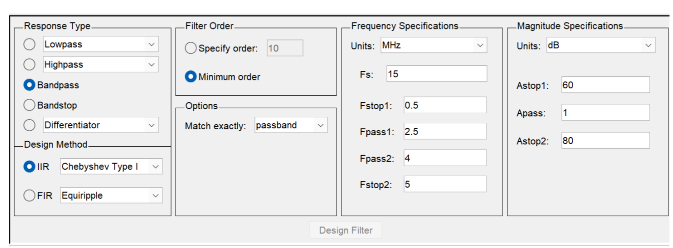

Figure 10: Chebyshev Filter Numbers

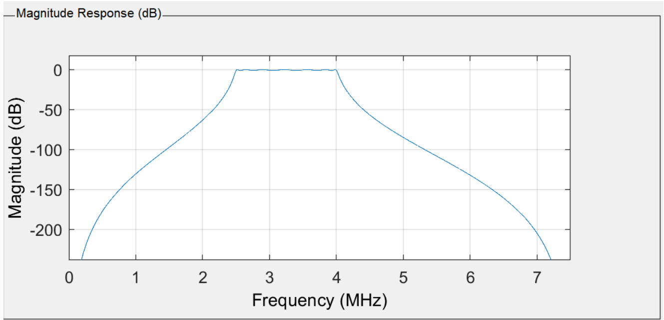

Figure 11: Chebyshev Magnitude Spectrum

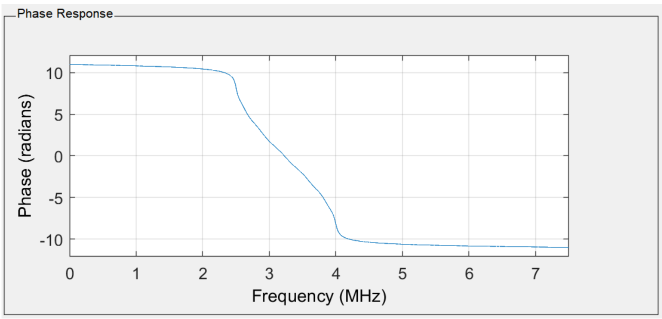

Figure 12: Chebyshev Phase Spectrum

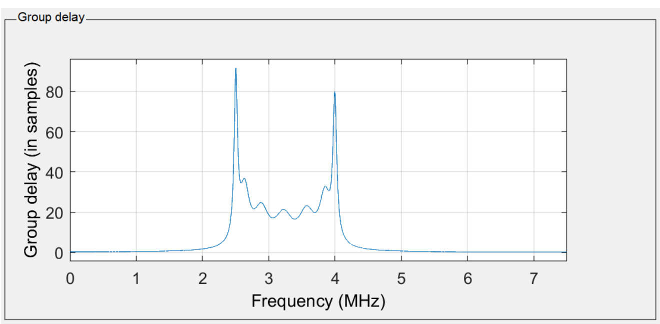

Figure 13: Chebyshev Group Delay

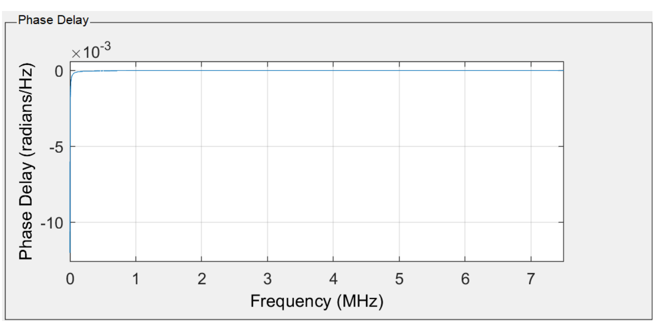

Figure 14: Chebyshev Phase Delay

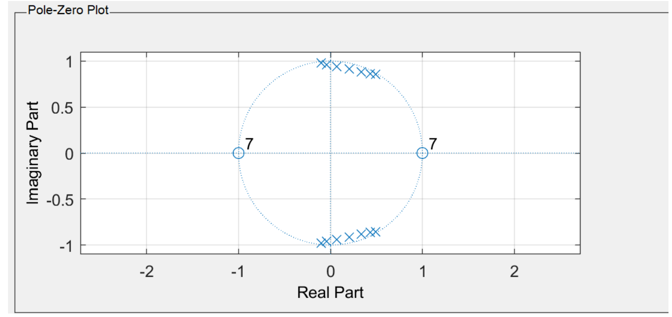

Figure 15: Chebyshev Pole Zero Plot

VI. Task 2: Apply Filters on Ultrasound RF Signals

A. Original Unfiltered Data:

The original B-mode image exhibits significant speckle noise, reducing contrast and obscuring anatomical boundaries.

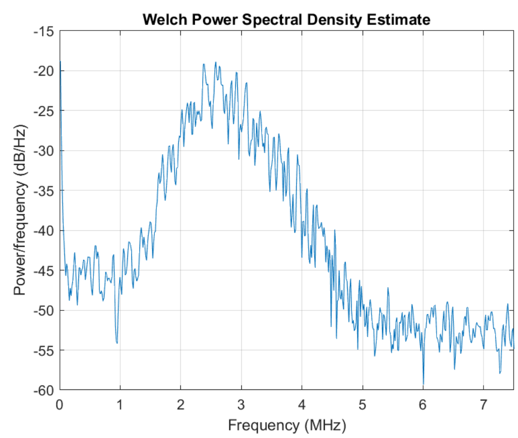

Figure 16: Welch Power Spectral Density Estimate Original

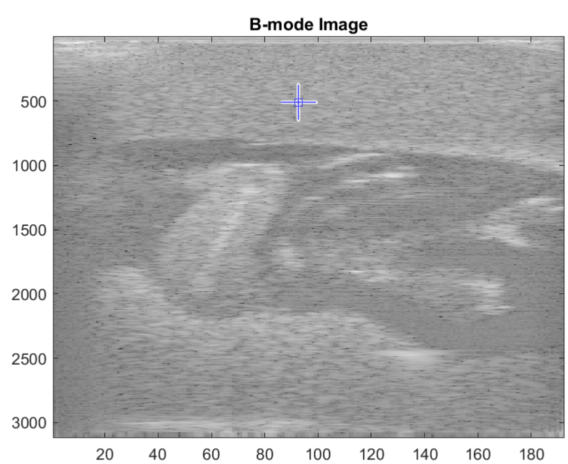

Figure 17: Original B-mode Image

B. Butterworth Filter Data:

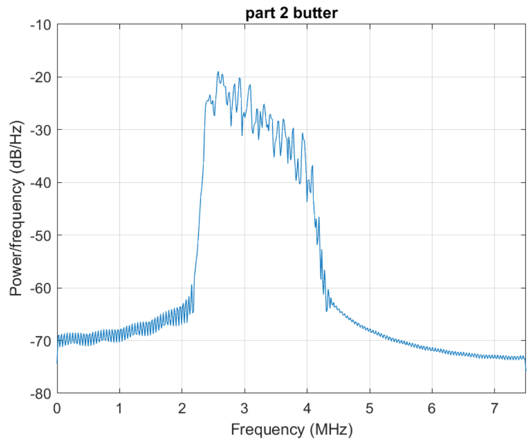

Figure 18: Welch Power Spectral Density Estimate Butterworth
Top SSI = 4.637
Bottom SSI = 1.638

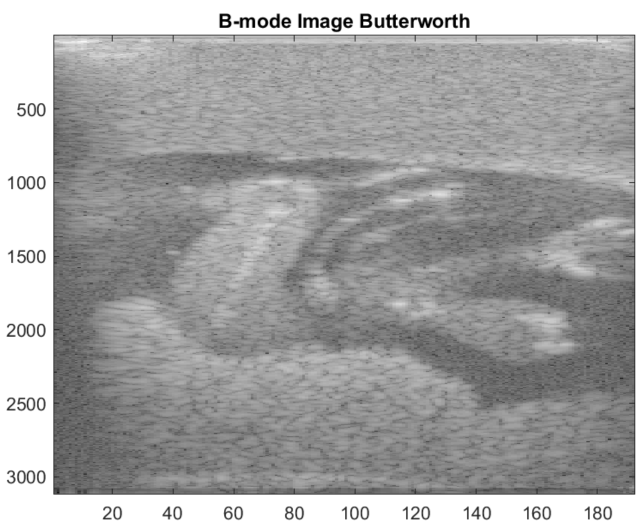

Figure 19: Butterworth B-mode Image

C. Chebyshev Type-1 Filter data:

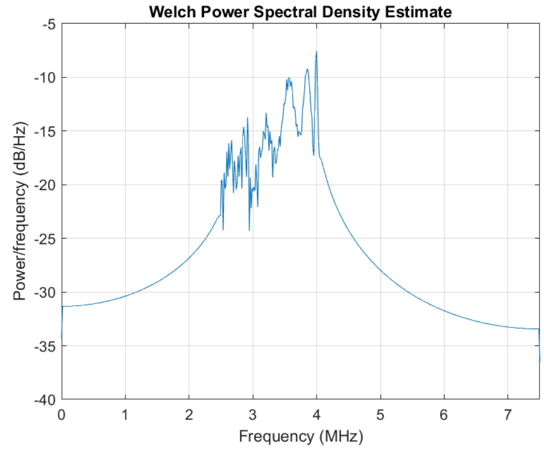

Figure 20: Welch Power Spectral Density Estimate Butterworth
Top SSI = 4.927
Bottom SSI = 2.537

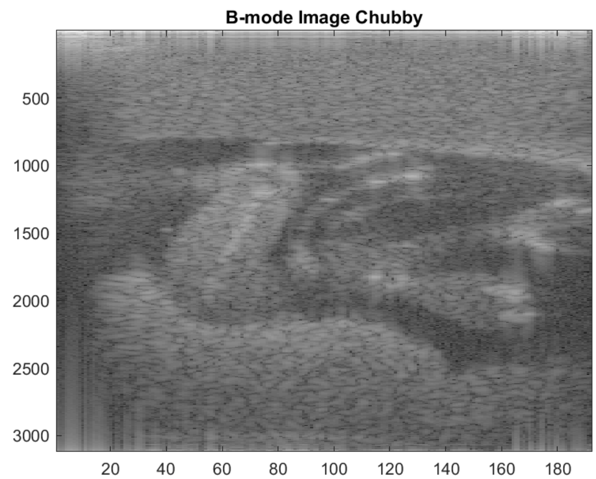

Figure 21: Chebyshev B-mode Image

VII. Task 3: Anterior Placenta

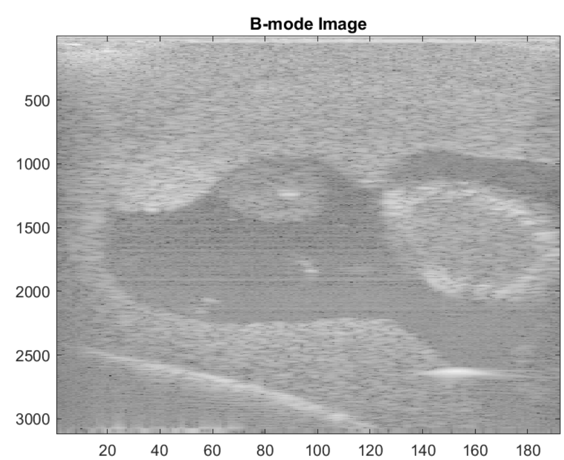

Figure 22: Original B-mode Image (anterior placenta)

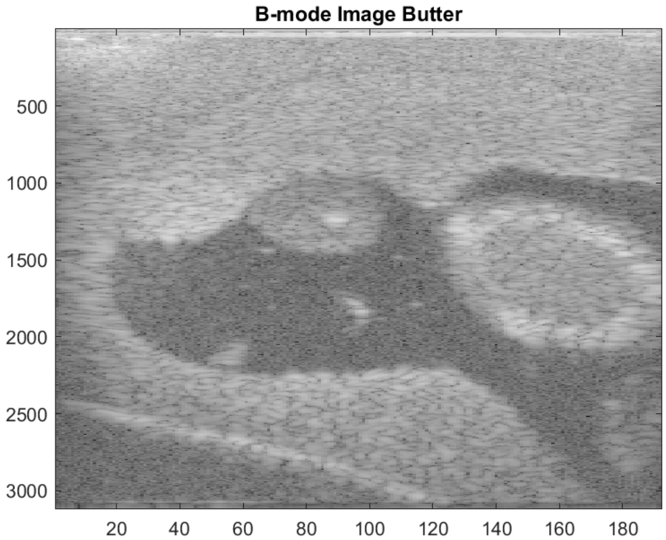

Figure 23: Butterworth B-mode Image (anterior placenta)

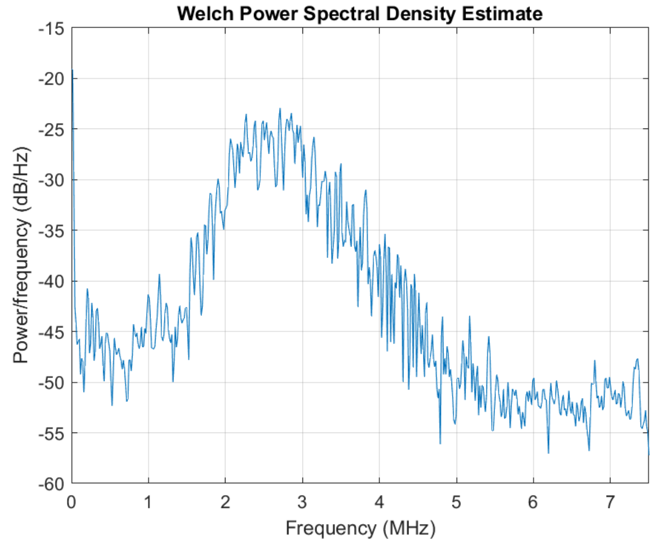

Figure 25: Welch Power Spectral Density Estimate Original
Top SSI = 4.637
Bottom SSI = 1.638

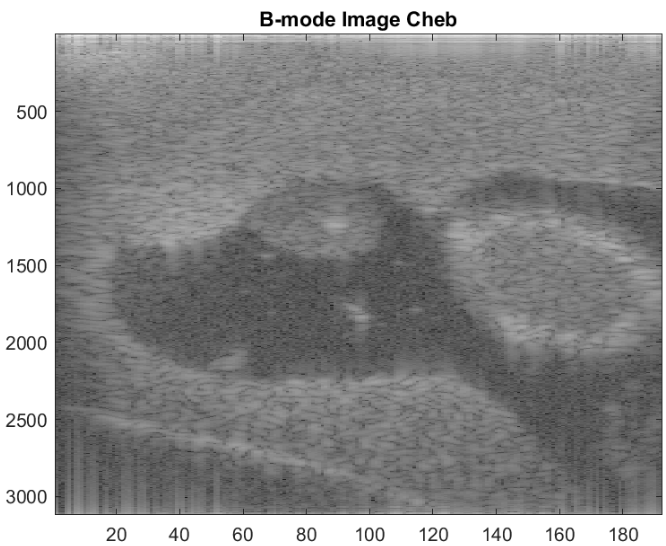

Figure 24: Cheb B-mode Image (anterior placenta)

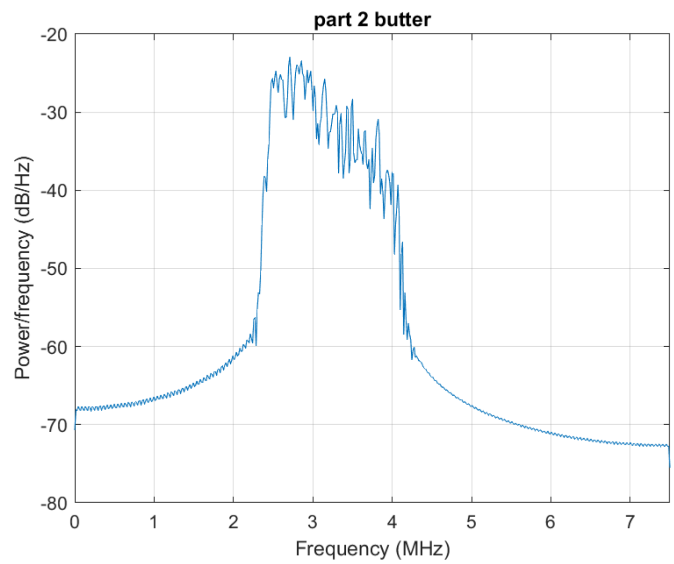

Figure 27: Welch Power Spectral Density Estimate Butterworth
Top SSI = 4.0100
Bottom SSI = 0.9799

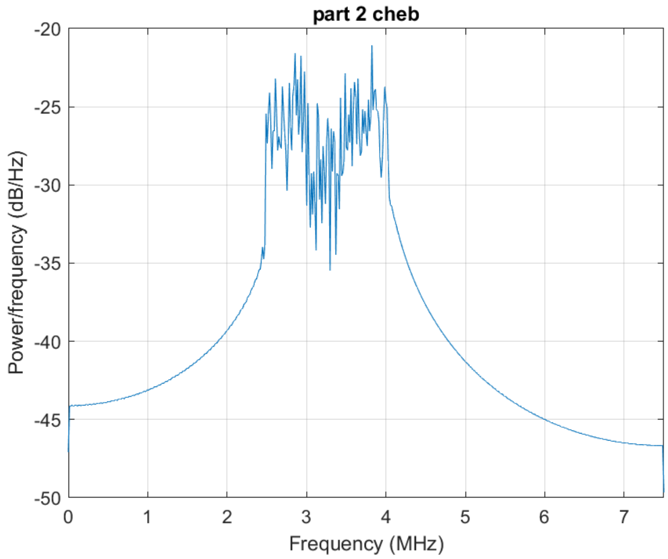

Figure 26: Welch Power Spectral Density Estimate Cheb

Top SSI = 4.0049

Bottom SSI = 0.9473

VIII. Results

A. Filter Design and Frequency Response Characteristics (Task 1)

Figures 6 through 9 present the design and frequency response of the Butterworth filter, while Figures 11 through 15 depict the Chebyshev Type I filter characteristics. Both filters were designed using MATLAB's Filter Designer, with passband and stopband parameters determined through Welch Power Spectral Density (PSD) estimates (Figure 3).

Magnitude Response (Figures 6 & 11): The Butterworth filter exhibits a smoothly decaying magnitude response with no passband ripples, characteristic of its maximally flat design. This ensures that amplitude variations within the passband are minimized, preserving signal integrity. The Chebyshev filter, by contrast, shows distinct ripples in the passband — a design trade-off that allows for a sharper transition between the passband and stopband, improving out-of-band noise attenuation.

Phase Response (Figures 7 & 12): The Butterworth filter has a nonlinear but smooth phase response, meaning that phase shifts accumulate gradually across frequencies. The Chebyshev filter shows abrupt phase changes near the cutoff frequency, reflecting its steeper roll-off. Such phase irregularities can introduce temporal artifacts if not corrected.

Group Delay and Phase Delay (Figures 8 & 13): The Butterworth filter maintains relatively consistent group and phase delays across the passband, preserving the temporal alignment of signal components. The Chebyshev filter, on the other hand, exhibits more variation in group delay near the band edges, which can result in signal distortion, particularly in applications sensitive to timing.

Pole-Zero Plots (Figures 9 & 14): Butterworth poles are symmetrically distributed in the left half of the z-plane, providing excellent stability and a smooth response. Chebyshev poles are positioned closer to the unit circle, which enables sharper frequency discrimination but increases sensitivity to parameter variations and potential numerical instability.

Summary: The Butterworth filter offers smoother, more stable behavior and is preferable when maintaining amplitude and phase fidelity is critical. The Chebyshev filter, with its aggressive frequency cutoff, is advantageous for applications requiring strong noise suppression near the band edges.

B. B-mode Image Results (Task 2)

Figures 4 (original), 19 (Butterworth), and 21 (Chebyshev) present the B-mode ultrasound images generated from the unfiltered and filtered RF data.

Original B-mode Image (Figure 4): The image exhibits prominent speckle noise, with granular artifacts that obscure tissue boundaries and hinder anatomical interpretation. High-frequency speckle patterns reduce contrast and limit the visibility of fine structures.

Butterworth B-mode Image (Figure 19): Following Butterworth filtering, the image shows significant noise suppression. Speckle granularity is markedly reduced, resulting in a smoother texture across homogeneous tissue regions. However, the slow roll-off of the filter may slightly blur fine edges, which is a typical trade-off of flat-response filters.

Chebyshev B-mode Image (Figure 21): The Chebyshev-filtered image demonstrates improved edge preservation while achieving moderate speckle suppression. The sharper frequency cutoff better isolates the desired signal, but minor artifacts from the passband ripple are occasionally visible near sharp tissue interfaces.

Observation: In Task 2, the Butterworth filter provided superior despeckling performance and produced a cleaner, diagnostically improved image compared to the Chebyshev filter.

C. Anterior Placenta Results (Task 3)

Figures 22–26 display the results on the anterior placenta dataset.

Butterworth (Figure 23): Noise suppression remains consistent, but the filter slightly reduces the visibility of subtle placental textures, making it less ideal for evaluating fine details.

Chebyshev (Figure 24): The Chebyshev filter excels here, delivering excellent noise suppression while maintaining fine anatomical details, including subtle boundaries within the placenta. Its sharper frequency discrimination allows preservation of high-frequency image components important for clinical evaluation.

Observation: For the anterior placenta dataset, the Chebyshev filter outperformed the Butterworth filter, striking a more effective balance between speckle reduction and feature preservation.

D. Power Spectral Density Analysis

Figures 16–18 illustrate the Welch PSD estimates:

Original (Figure 16): A broad frequency spectrum containing both useful signal and noise components.

Butterworth (Figure 17): A gradual attenuation of high-frequency noise, effectively narrowing the signal bandwidth and improving the signal-to-noise ratio.

Chebyshev (Figure 18): Sharper suppression of out-of-band frequencies, delivering a cleaner frequency profile but potentially increasing sensitivity to signal fluctuations.

E. Speckle Suppression Index (SSI) Comparison

Filter		**Top SSI**	**Bottom SSI**
ButterWorth	Task 1	4.637	1.638
	Task 2	4.927	2.537
Chebyshev	Task 1	4.0100	0.9799
	Task 2	4.0049	0.9473

Interpretation:

Task 2 (homogeneous tissue): Butterworth achieved lower SSI, confirming better speckle suppression.

Task 3 (anterior placenta): Chebyshev achieved slightly lower SSI, indicating better performance in heterogeneous, high-detail regions.

Clinical significance: These results highlight that filter selection should be tailored to the anatomical target and the clinical goal — smoother, homogeneous regions benefit from Butterworth filtering, while complex regions with critical fine details favor Chebyshev filtering.

IX. Limitations and Future Work

A. Limitations

While the Butterworth and Chebyshev Type I filters demonstrated effective speckle reduction in ultrasound B-mode images, several limitations should be acknowledged:

- **Fixed filter parameters:** The filter designs relied on predetermined passband and stopband frequencies based on PSD analysis, which may not generalize optimally across all datasets or anatomical regions. Adaptive tuning could improve performance.

- **Trade-off between noise suppression and detail preservation:** Both filters present an inherent trade-off—while the Butterworth filter smooths homogeneous regions effectively, it may blur fine structures. Conversely, the Chebyshev filter preserves edges but introduces minor ripples and potential artifacts.

- **Limited anatomical coverage:** The study focused on general tissue regions and the anterior placenta. Additional anatomical sites, such as vascular structures or tumors, were not evaluated and may present unique challenges.

- **Quantitative metrics:** The evaluation primarily used the Speckle Suppression Index (SSI), which quantifies noise reduction but does not fully capture subjective or clinical image quality. Incorporating perceptual or clinical assessment metrics could provide a more comprehensive evaluation.

- **Computational constraints:** Although MATLAB offers a flexible environment for filter design and testing, real-time clinical applications would require optimization for speed and hardware constraints.

B. Future Work

Future research can address these limitations and further advance ultrasound image processing:

- **Adaptive filtering:** Implementing adaptive filter designs that automatically adjust parameters based on local image statistics could improve performance across heterogeneous tissue types.

- **Hybrid approaches:** Combining frequency domain filtering (e.g., Butterworth, Chebyshev) with spatial or machine learning–based despeckling methods may yield superior noise suppression without compromising anatomical detail.

- **Expanded anatomical validation:** Evaluating filter performance across a wider range of clinical cases, including fetal, cardiac, and vascular imaging, would increase generalizability and clinical relevance.

- **Subjective evaluation:** Incorporating radiologist or sonographer assessments alongside quantitative metrics would provide a more holistic understanding of clinical impact.

- **Real-time implementation:** Optimizing algorithms for integration into ultrasound machines, possibly using GPU acceleration or embedded systems, could enable real-time despeckling in clinical workflows.

X. Conclusion

This project demonstrated the effective use of Butterworth and Chebyshev Type I filters for speckle noise reduction in ultrasound imaging. MATLAB-based filter design, application, and evaluation showed that the Butterworth filter performed best for homogeneous tissue regions by producing smoother images and achieving superior speckle suppression. Conversely, in the anterior placenta dataset, the Chebyshev filter provided optimal performance, maintaining anatomical detail while reducing noise.

These findings emphasize the importance of context-specific filtering strategies in medical imaging. Future work could explore adaptive or hybrid filtering approaches, real-time implementation, and machine learning–based despeckling techniques to further improve ultrasound image quality across diverse clinical applications.the robustness of both filters across different anatomical regions.

Overall, the Chebyshev filter is preferable when stronger suppression is needed, while the Butterworth filter balances noise reduction with image smoothness.