CMPE362 Homework 3: Noise Removal using Digital Filters

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Objective

The objective of this assignment is to design and analyze digital bandstop filters to remove narrowband noise from an audio signal. I explore both FIR and IIR filter design techniques in MATLAB and evaluate their effectiveness based on their frequency response, spectrograms, and subjective performance.

1. Spectrogram Analysis

To identify the noise frequency band, I analyzed the spectrogram of the original audio signal using the MATLAB function `spectrogram()`. The spectrogram revealed a persistent horizontal band of noise between approximately 3.8 kHz and 4.9 kHz, especially visible during silent regions of the recording.

Estimated Noise Band: [3800 Hz, 4900 Hz]

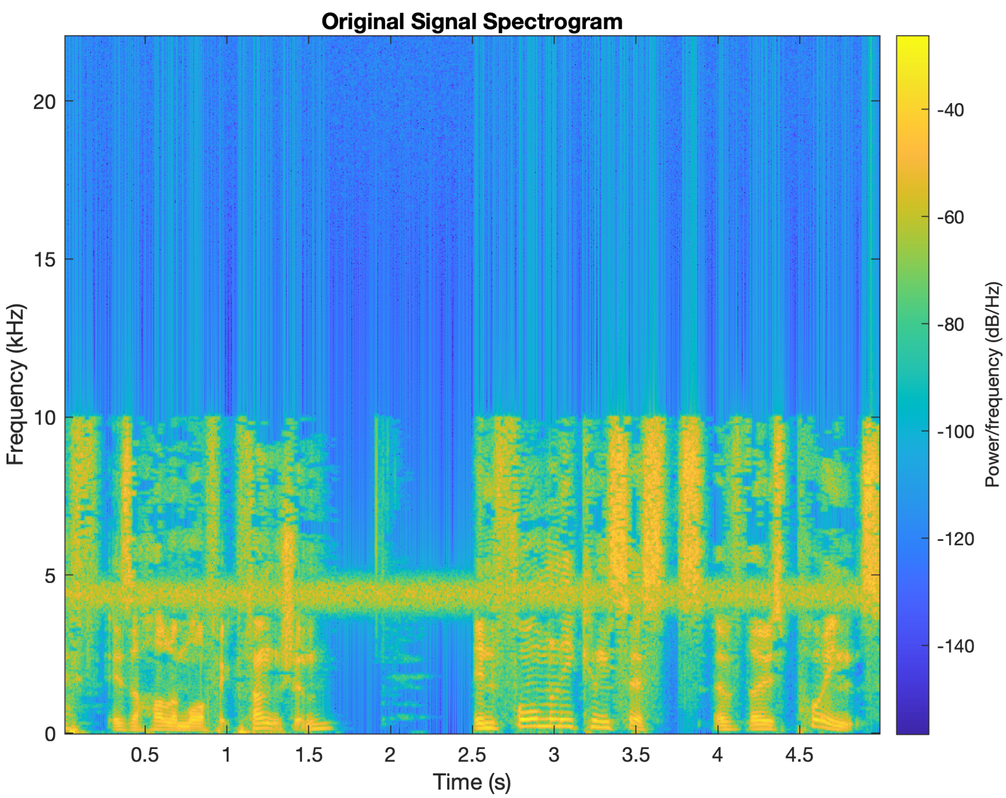

Figure 1: Spectrogram of the original noisy signal. Noise is most visible in the 3.8–4.8 kHz range.

2. FIR Filter Design

A 256th-order FIR bandstop filter was designed using the `fir1()` function with normalized cutoff frequencies defined as

$$W_n = \left[\frac{f_1 - 500}{f_s/2}, \frac{f_2 + 500}{f_s/2}\right]$$

where $f_1 = 3800$ Hz, $f_2 = 4800$ Hz, and f_s is the sampling frequency. This FIR filter effectively attenuates the target frequency band while preserving linear phase characteristics.

3. IIR Filter Design

I designed three IIR bandstop filters for the same frequency range using the following methods:

- Butterworth filter using `butter()`, with order $n = 7$
- Chebyshev Type I filter using `cheby1()`, with order $n = 6$ and passband ripple $R_p = 0.1$ dB
- Elliptic filter using `ellip()`, with order $n = 6$, passband ripple $R_p = 0.1$ dB, and stopband attenuation 40 dB

I chose these values to obtain the lowest possible order at which the noise becomes almost inaudible in the audio.

4. Frequency Response and Pole-Zero Plots

I plotted the log-magnitude frequency responses of each filter using `freqz()`, and pole-zero diagrams of the IIR filters using `zplane()`. The frequency responses show that all IIR filters achieved effective attenuation around the noise band, with the elliptic filter offering the sharpest roll-off.

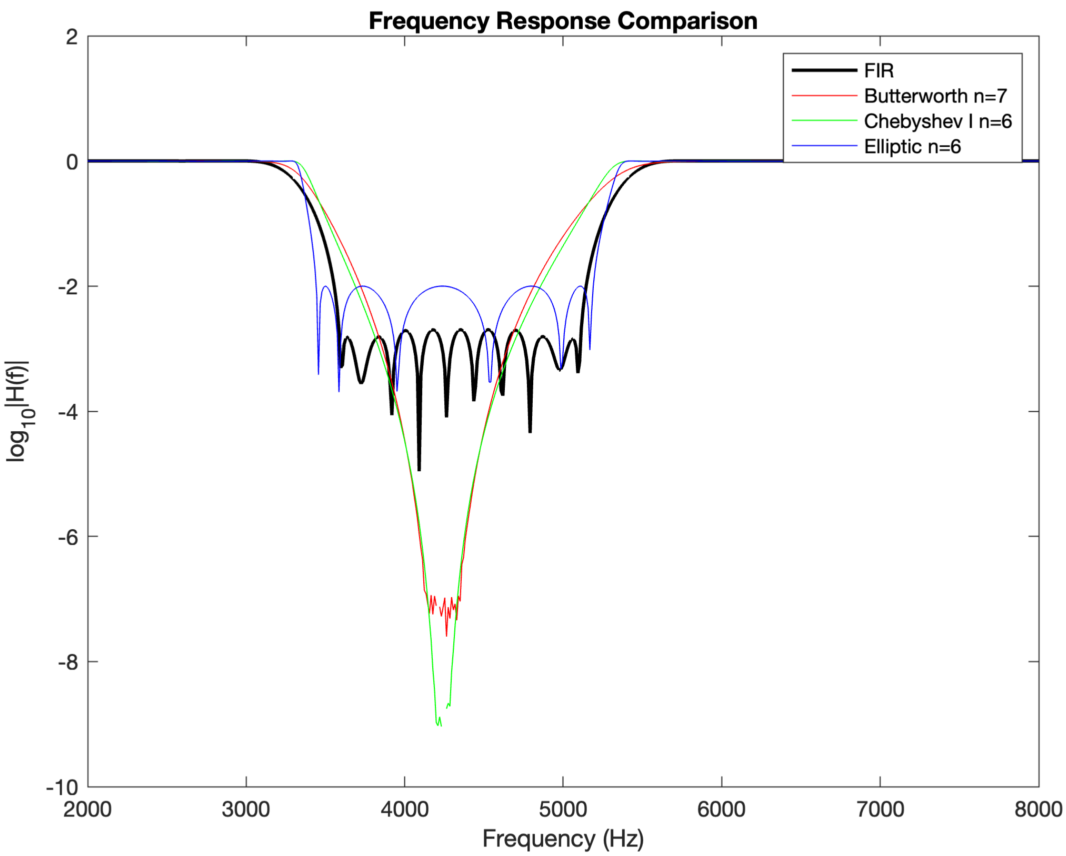

Figure 2: Frequency response comparison for selected filter orders.

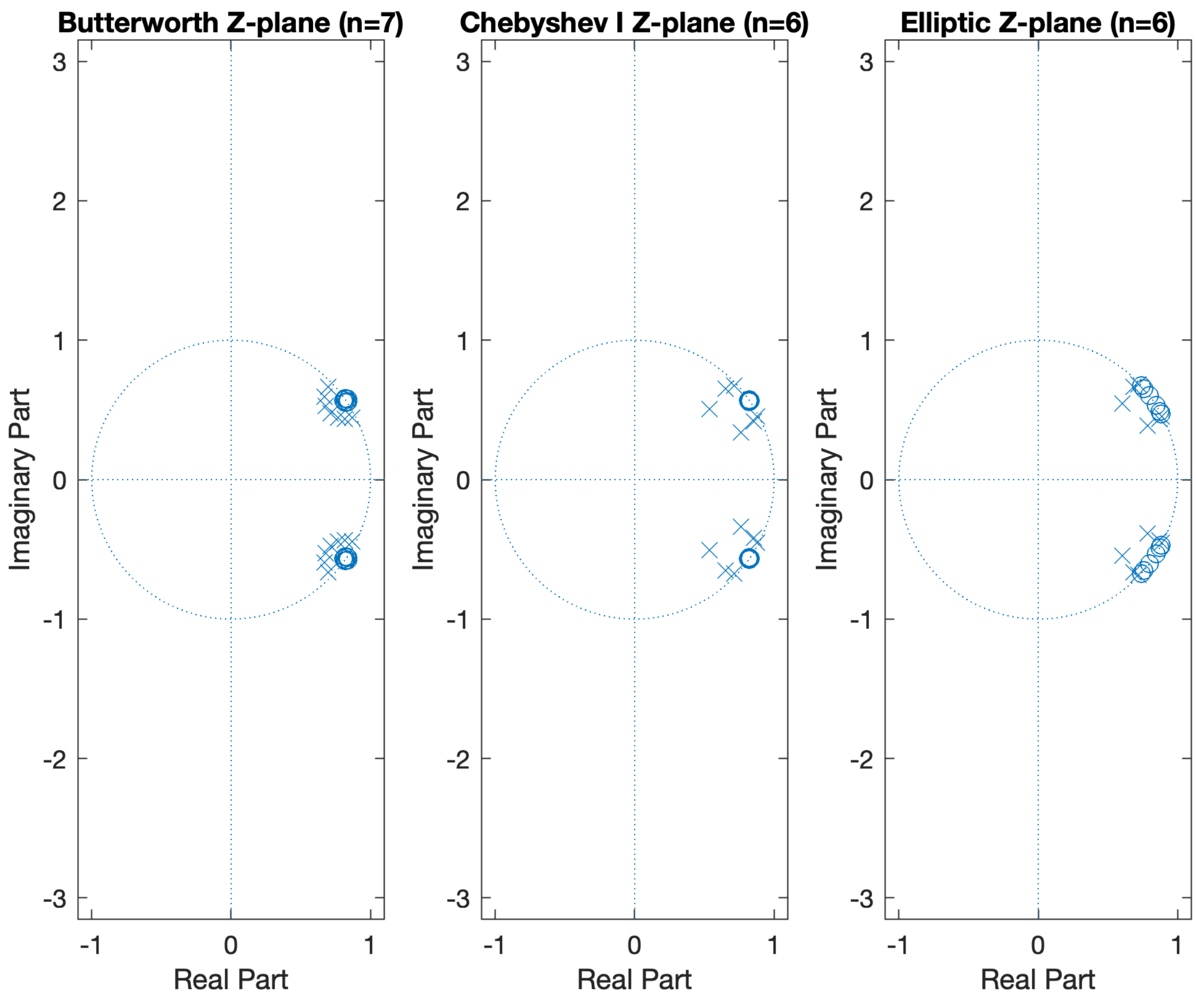

Figure 3: Pole-zero plots of Butterworth, Chebyshev I, and Elliptic filters.

5. Spectrograms After Filtering

After applying each filter to the audio signal, I generated the spectrograms of the filtered signals. The FIR filter achieved the most uniform suppression. Among IIR designs, Chebyshev Type I and Elliptic filters closely matched FIR performance while using significantly lower orders. Butterworth required a slightly higher order to reach comparable suppression.

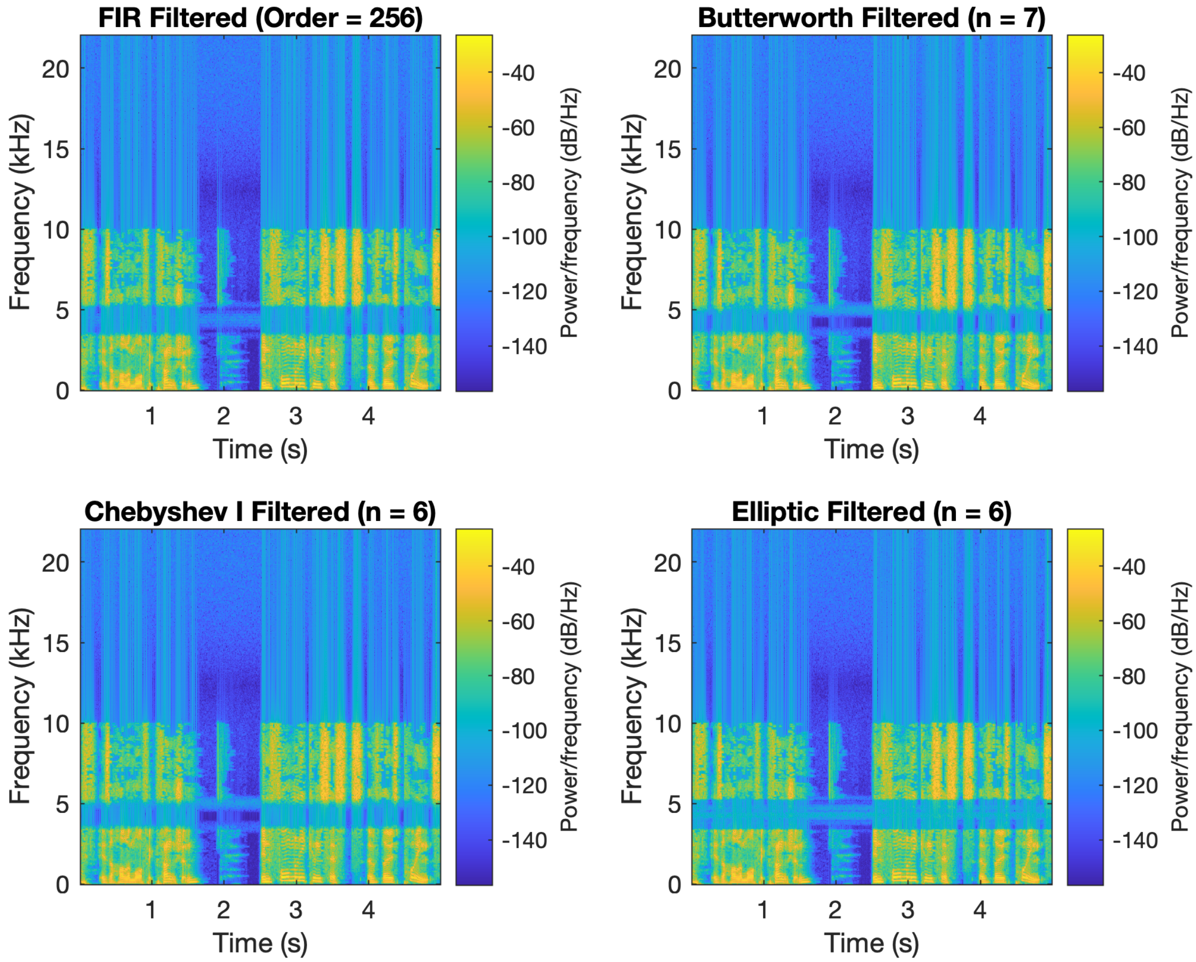

Figure 4: Spectrograms after filtering with FIR and IIR filters.

6. Stability Analysis of IIR Filters

To assess numerical stability, I increased the order for each IIR filter until instability or audio corruption was observed. The smallest unstable orders were:

- Butterworth: 13
- Chebyshev Type I: 12
- Elliptic: 10

The frequency responses at these orders show excessive gain fluctuation and loss of stopband selectivity, confirming instability.

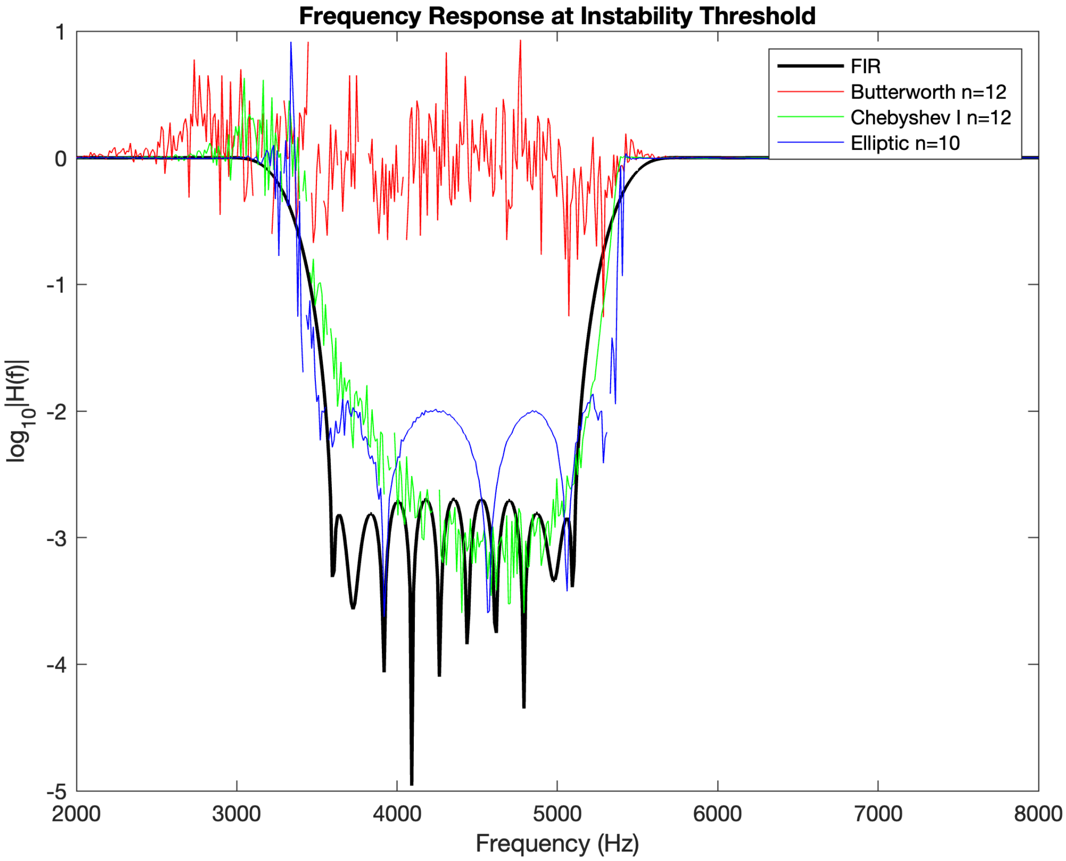

Figure 5: Frequency responses of IIR filters near instability threshold.

Conclusion

Through spectrogram analysis and filter design, I successfully identified and removed a narrowband noise between 3.8–4.9 kHz. FIR filtering with order 256 provided excellent suppression with linear phase. Among IIR filters, Chebyshev and Elliptic achieved comparable suppression using lower orders. Final chosen parameters were:

- Butterworth: 7
- Chebyshev Type I: 6
- Elliptic: 6

These choices offered a strong balance between performance, efficiency, and numerical stability.