Group10: IIR Filters for Audio Noise Removal

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Background

Infinite Impulse Response (IIR) filters are fundamental in digital signal processing, characterized by feedback mechanisms that allow their impulse responses to last indefinitely. The transfer function in the z-domain is:

$$H(z) = \frac{\sum_{k=0}^{N} b_k z^{-k}}{1 + \sum_{k=n}^{M} a_k z^{-k}} \tag{1}$$

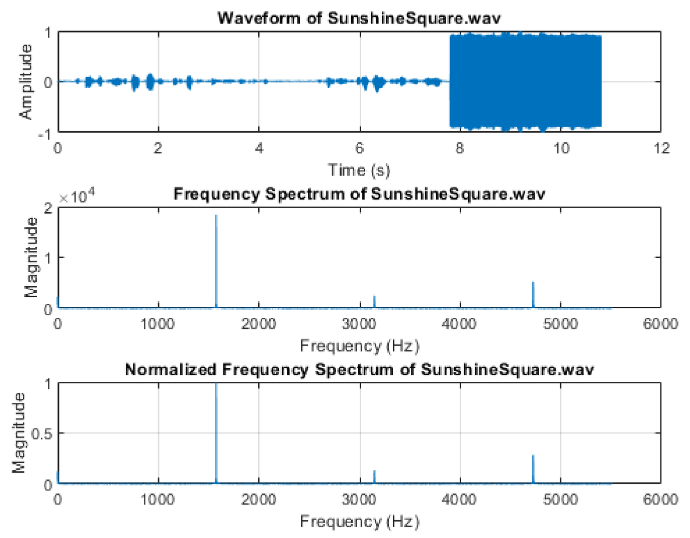
The **zeros** and **poles** of $H(z)$ determine the filter's frequency response. Strategically placing zeros and poles in the z-plane allows specific frequency components to be attenuated or amplified.

A **notch filter** attenuates a narrow band of frequencies while leaving the rest of the spectrum relatively unaffected. This is achieved by:

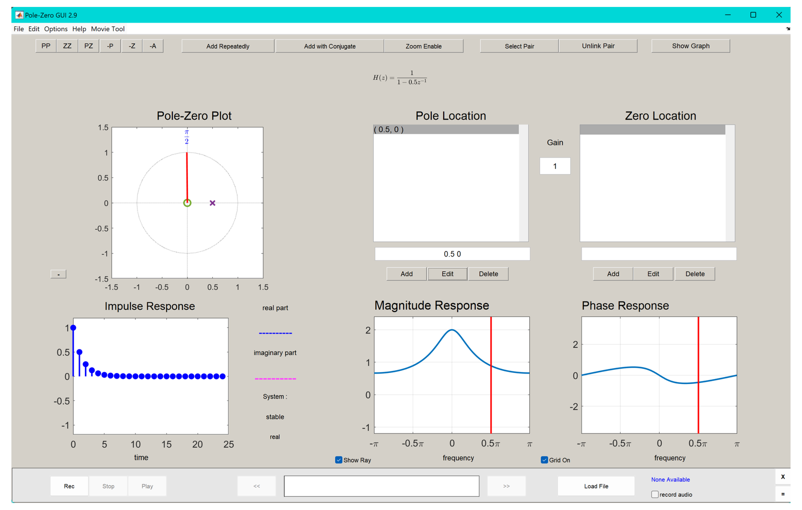
- Placing **zeros** on the unit circle at the notch frequency ω_0.
- Placing **poles** near the zeros inside the unit circle to maintain filter stability.

This selective attenuation contrasts with standard low-pass or high-pass filters, which broadly attenuate frequencies beyond a cutoff frequency.

Introduction: Audio and PeZ



(a) Original Singal



(b) PeZ GUI

Method

Our approach involved the following steps:

1. Frequency Analysis Using Fourier Transform
   - Performed a Fourier Transform on the recorded audio signal to convert it from the time domain to the frequency domain.
   - Identified prominent peaks in the frequency spectrum corresponding to noise frequencies.
2. Design of the IIR Notch Filter
   - Placed zeros on the unit circle at the identified noise frequency ω_0 to create a notch.
   - Placed poles near the zeros inside the unit circle to sharpen the notch and maintain filter stability.
   - Used MATLAB's *PeZ* GUI tool to manipulate zeros and poles and observe their effects on the filter's frequency response.
3. Design of Low-Pass Filters for Comparison
   - Designed an **IIR low-pass filter** using MATLAB's *butter* function with an appropriate cutoff frequency:

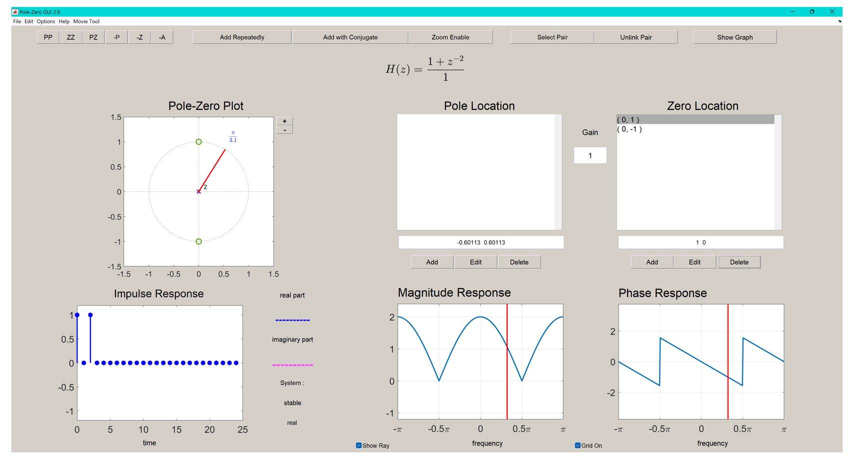
     $$[b, a] = \text{butter}(n, f) \tag{2}$$

   - Designed an **FIR low-pass filter** using MATLAB's *fir1* function:

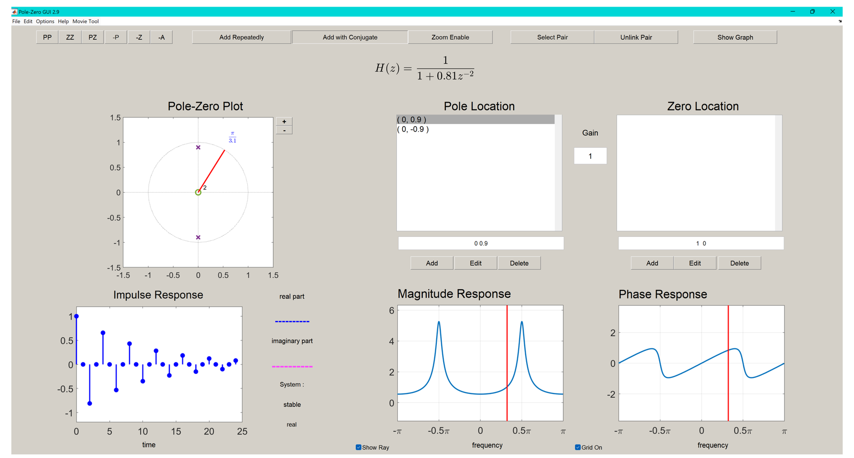
     $$b = \text{fir1}(n, f) \tag{3}$$

Finding in Lab Exercise

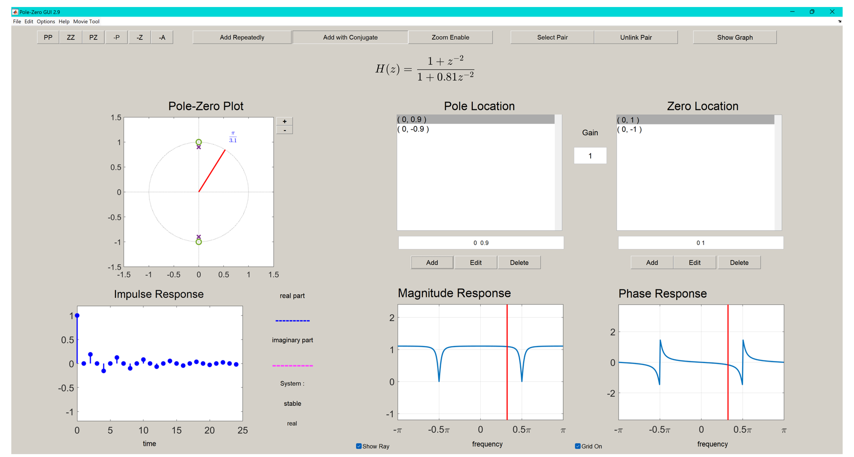
Using the PeZ GUI tool in MATLAB, we investigated how the placement of poles and zeros affects the frequency response of IIR filters:



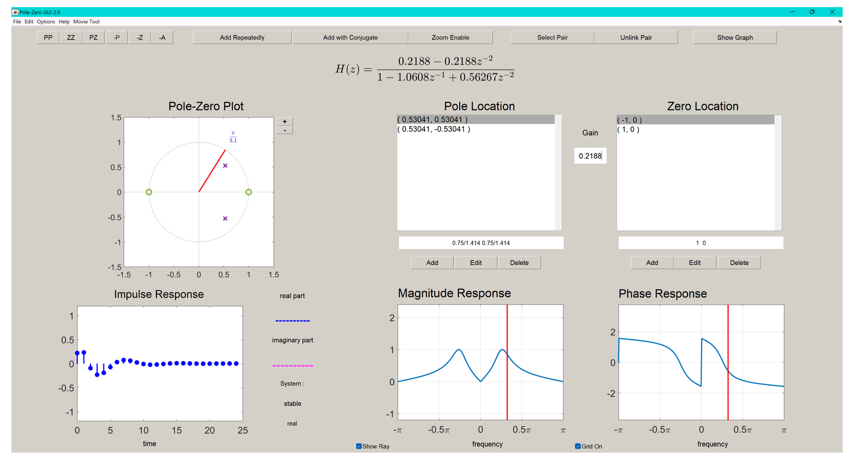
(a) **Zeros Only**: Zeros on the unit circle fully attenuate specific frequencies. Moving them closer to the origin broadens attenuation but weakens its effectiveness.



(b) **Poles Only**: Poles near the unit circle amplify specific frequencies, creating sharp resonance peaks in the frequency response.



(c) **Poles and Zeros**: Combining zeros on the unit circle with nearby poles inside it creates notch filters, sharply attenuating unwanted frequencies while preserving stability.



(d) **Poles and Zeros**: Zeros on the unit circle suppress specific frequencies, while nearby poles amplify frequencies near their locations. This creates sharp resonance peaks and deep notches in the frequency response, enabling selective frequency shaping with stability.

These experimental observations demonstrate how strategic placement of poles and zeros can be utilized to design filters with desired frequency characteristics, offering advantages over standard low-pass and high-pass filters in preserving the integrity of the original signal.

Audio Compare

Original Audio

Notch Filter (IIR)

Low Pass Filter (IIR) $Order = 6$

Low Pass Filter (IIR) $Order = 10$

Low Pass Filter (FIR) $Order = 6$

Low Pass Filter (FIR) $Order = 50$

Discussion

We compared the performance of **IIR** and **FIR filters** for removing high-frequency noise from audio signals. Using **Fourier analysis**, we identified that the noise was concentrated around specific frequencies. This insight led us to choose the **notch filter** as the optimal solution.

- **Preserving Signal Integrity**: Maintained the strength and clarity of the original audio signal.
- **Selective Noise Suppression**: Effectively suppressed noise at targeted frequencies without affecting the rest of the spectrum. The **Low-pass** filter will also reduce the human voice.

For **FIR filters**, achieving similar noise suppression required a very high filter order. The **IIR notch filter**, therefore, strikes a balance between computational efficiency and effective noise attenuation, making it an excellent choice for applications requiring selective frequency suppression.

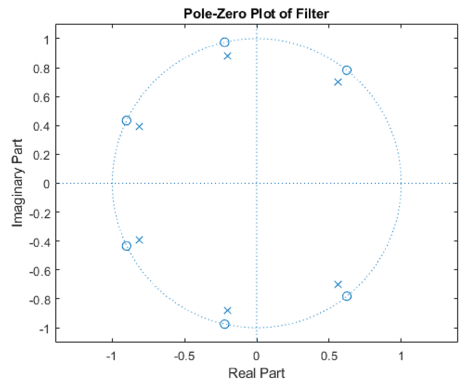


Figure 3. Notcha Filter

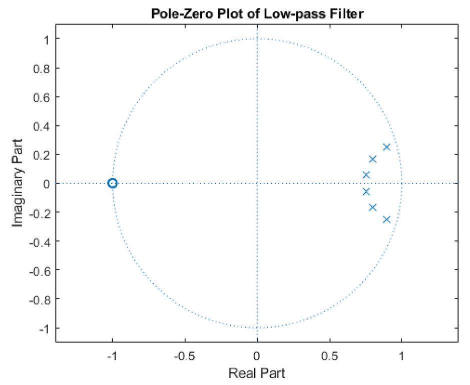


Figure 4. Low-Pass Filter (IIR)

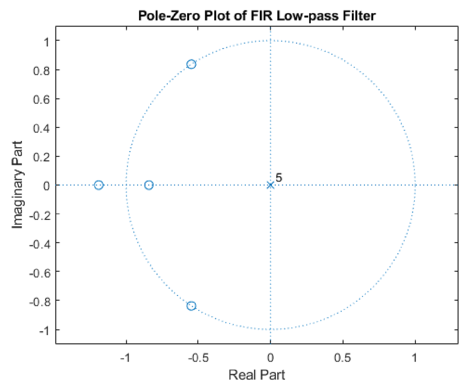


Figure 5. Low-Pass Filter (FIR by Hann)

Contributions

Connor: Played a leading role in completing the Lab Exercises.

Sumaiya: Contributed by writing the Lab Exercise and Mini-Project code portions.

Xiangjian: Designed the poster and conducted comparative experiments on different filters.