IBEHS 3A03 Assignment #4:

Fourier Analysis of Biomedical Signals

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# PURPOSE

In this assignment, we designed an IIR and an FIR filter to reject the unwanted frequency component(s) from the electroencephalogram (EEG) signals and the vertical ground reaction force (VGRF) signal. Using our knowledge of filters, we use the custom function *fourier\_dt( )* to analyze the different scenarios of using different filters on the same signal with MATLAB.

# METHODOLOGY

## Part A: EEG Data Analysis

### Task A1) Plots the input time-domain waveform of EEG

The time-domain EEG signal was loaded and plotted alongside the IIR and FIR filtered EEG signal (see Task A3) using the plot() function.

**Table 1.** Variables used in Task A1 in order of implementation.

| **Variable** | **Assignment / Location Used** | **Description** |
| --- | --- | --- |
| EEGa4 | load EEGdata\_assignment4.mat | Given EEG signal |

### Task A2) Plot the magnitude and phase spectra of EEG

The custom function, fourier\_dt(), was used to produce the magnitude spectrum, phase spectrum, and the frequencies of the discrete fourier transform (DFT) of the given EEG signal. The magnitude and phase spectrums were then plotted alongside the magnitude and phase spectrum of the IIR and FIR filtered EEG signal (see Task A4).

**Table 2.** Variables used in Task A2 in order of implementation.

| **Variable** | **Assignment / Location Used** | **Description** |
| --- | --- | --- |
| EEGa4 | load EEGdata\_assignment4.mat | Given EEG signal |
| Fs | load EEGdata\_assignment4.mat | EEG signal sampling frequency |
| MEEG | [MEEG,phEEG,fEEG] = fourier\_dt(EEGa4,Fs,"half"); | Magnitude spectrum of the EEG signal |
| phEEG | [MEEG,phEEG,fEEG] = fourier\_dt(EEGa4,Fs,"half"); | Phase spectrum of the EEG signal |
| fEEG | [MEEG,phEEG,fEEG] = fourier\_dt(EEGa4,Fs,"half"); | Frequencies of the DFT of the EEG signal |

### Task A3) Plots the output time-domain waveform with the filter

The time-domain EEG signal was filtered using the filter() MATLAB function and the filters created with MATLAB Signal Processing Toolbox’s Filter Designer. For the EEG analysis, ()an IIR and FIR notch filters meant to remove the 50 Hz ac power noise from the signal were used. The resulting time-domain filter outputs were plotted alongside the original EEG signal (see Task A1).

**Table 3.** Variables used in Task A3 in order of implementation.

| **Variable** | **Assignment / Location Used** | **Description** |
| --- | --- | --- |
| EEGa4 | load EEGdata\_assignment4.mat | Given EEG signal |
| part1IIR | load part1IIR.mat | IIR Filter |
| part1FIR | load part1FIR.mat | FIR Filter |
| IIRFilteredEEG | IIRFilteredEEG = filter(part1IIR,EEGa4); | EEG signal filtered through the IIR filter |
| FIRFilteredEEG | FIRFilteredEEG = filter(part1FIR,EEGa4); | EEG signal filtered through the FIR filter |

### Task A4) plot the magnitude and phase spectra of the output waveform

The custom function, fourier\_dt(), was used to produce the magnitude spectrum, phase spectrum, and the frequencies of the discrete fourier transform of the IIR and FIR filtered EEG signal. The resulting magnitude and phase spectrums were then plotted alongside the magnitude and phase spectrum of unfiltered EEG signal (see Task A1).

**Table 4.** Variables used in Task A4 in order of implementation.

| **Variable** | **Assignment / Location Used** | **Description** |
| --- | --- | --- |
| EEGa4 | load EEGdata\_assignment4.mat | Given EEG signal |
| Fs | load EEGdata\_assignment4.mat | EEG signal sampling frequency |
| part1IIR | load part1IIR.mat | IIR Filter |
| part1FIR | load part1FIR.mat | FIR Filter |
| IIRFilteredEEG | IIRFilteredEEG = filter(part1IIR,EEGa4); | EEG signal filtered through the IIR filter |
| FIRFilteredEEG | FIRFilteredEEG = filter(part1FIR,EEGa4); | EEG signal filtered through the FIR filter |
| MIIRFilteredEEG | [MIIRFilteredEEG,phIIRFilteredEEG,fIIRFilteredEEG] = fourier\_dt(IIRFilteredEEG,Fs,"half"); | Magnitude spectrum of the IIR filtered EEG |
| phIIRFilteredEEG | Phase spectrum of the IIR filtered EEG |
| fIIRFilteredEEG | Frequencies of the DFT of the IIR filtered EEG signal |
| MFIRFilteredEEG | [MFIRFilteredEEG,phFIRFilteredEEG,fFIRFilteredEEG] = fourier\_dt(FIRFilteredEEG,Fs,"half"); | Magnitude spectrum of the FIR filtered EEG |
| phFIRFilteredEEG | Phase spectrum of the FIR filtered EEG |
| fFIRFilteredEEG | Frequencies of the DFT of the FIR filtered EEG signal |

**IIR EGG Filter**

|  | **Specifications** |
| --- | --- |
| Response Type | Bandstop |
| Design Method | Chebyshev Type II |
| Filter Order | Minimum Order (8) |
| Match Exactly | Stopband |
| Fs | 200 |
| Fpass1 | 49.5 |
| Fstop1 | 49.9 |
| Fstop2 | 50.1 |
| Fpass2 | 50.5 |
| Apass1 | 0.5 |
| Astop | 60 |
| Apass2 | 0.5 |

**Table 5.** Filter specifications for IIR EGG filter.

**FIR EGG Filter**

| Response Type | Bandstop |
| --- | --- |
| Design Method | Equiripple |
| Filter Order | Minimum Order (194) |
| Density Factor | 20 |
| Fs | 200 |
| Fpass1 | 47.5 |
| Fstop1 | 49.9 |
| Fstop2 | 50.1 |
| Fpass2 | 52.5 |
| Apass1 | 0.5 |
| Astop | 60 |
| Apass2 | 0.5 |

**Table 6.** Filter specifications for FIR EGG filter.

## Part B: VGRF Data Analysis

### Task B1) Plots the input time-domain waveform of VGRF

Loaded the VGRF signal from the file and plots it. Table 7 describes the variables used for this task.

**Table 7.** Variables used in Task B1 in order of implementation.

| **Variable** | **Assignment / Location Used** | **Description** |
| --- | --- | --- |
| VGRF | load VGRFdata\_assignment4.mat | The input signal |

### Task B2) Plot the magnitude and phase spectra of VGRF

The custom function, fourier\_dt(), was used to produce the magnitude spectrum, phase spectrum, and the frequencies of the discrete fourier transform of the entire VGRF signal. Then plots the magnitude and phase spectrum. Table 8 describes the variables used for this task.

**Table 8.** Variables used in Task B2 in order of implementation.

| **Variable** | **Assignment / Location Used** | **Description** |
| --- | --- | --- |
| VGRF | load VGRFdata\_assignment4.mat | The input signal |
| Fs | 100 | Sampling rate |
| MVGRF | [MVGRF,phVGRF,fVGRF] = fourier\_dt(VGRF,Fs,"half") | Magnitude Spectrum of the VGRD signal |
| phVGRF | Phase Spectrum of the VGRD signal |
| fVGRF | Frequency of the VGRD signal |

### Task B3) Plots the output time-domain waveform with the filter

Loaded the VGRF signal, IIR filter and VIR filter from the files. Use filter to apply the filter onto the signal. Then plot the filtered signal. Table 9 describes the variables used for this task.

**Table 9.** Variables used in Task B3 in order of implementation.

| **Variable** | **Assignment / Location Used** | **Description** |
| --- | --- | --- |
| VGRF | load VGRFdata\_assignment4.mat | The input signal |
| VGRF\_IIR\_Filter2 | load VGRF\_IIR\_2.mat | The IIR filter for VGRF |
| Part2FIR | load Part2FIRFilter.mat | The VIR filter for VGRF |
| IIRFilteredVGRF | IIRFilteredVGRF = filter(VGRF\_IIR\_Filter2,VGRF) | The IIR-filtered VGRF signal |
| FIRFilteredVGRF | FIRFilteredVGRF = filter(Part2FIR,VGRF); | The VIR-filtered VGRF signal |

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### Task B4) plot the magnitude and phase spectra of the output waveform

Load the VGRF signal, the IIR filter and the VIR filter from the files. Then use the filter function to apply the filters onto the VGRF signal. The custom function, fourier\_dt(), was used to produce the magnitude spectrum, phase spectrum, and the frequencies of the discrete fourier transform of the filtered VGRF signal. Table 10 describes the variables used for this task.

**Table 10.** Variables used in Task B4 in order of implementation.

| **Variable** | **Assignment / Location Used** | **Description** |
| --- | --- | --- |
| Fs | 100 | Sampling rate |
| VGRF | load VGRFdata\_assignment4.mat | The input signal |
| VGRF\_IIR\_Filter2 | load VGRF\_IIR\_2.mat | The IIR filter for VGRF |
| IIRFilteredVGRF | IIRFilteredVGRF = filter(VGRF\_IIR\_Filter2,VGRF) | The IIR-filtered VGRF signal |
| MIIRFilteredVGRF | [MIIRFilteredVGRF,phIIRFilteredVGRF,fIIRFilteredVGRF] = fourier\_dt(IIRFilteredVGRF,Fs,"half")) | Magnitude Spectrum of the IIR-filtered VGRD signal |
| phIIRFilteredVGRF | Phase Spectrum of the IIR-filtered VGRD signal |
| fIIRFilteredVGRF | Frequency of the IIR-filtered VGRD signal |
| Part2FIR | load Part2FIRFilter.mat | The VIR filter for VGRF |
| FIRFilteredVGRF | FIRFilteredVGRF = filter(Part2FIR,VGRF) | The VIR-filtered VGRF signal |
| MFIRFilteredVGRF | [MFIRFilteredVGRF,phFIRFilteredVGRF,fFIRFilteredVGRF] = fourier\_dt(FIRFilteredVGRF,Fs,"half"); | Magnitude Spectrum of the VIR-filtered VGRD signal |
| phFIRFilteredVGRF | Phase Spectrum of the VIR-filtered VGRD signal |
| fFIRFilteredVGRF | Frequency of the VIR-filtered VGRD signal |

## 

The following depicts the specifications for designing the IIR and VIR filter.

**IIR VGRF Filter**

|  | **Specifications** |
| --- | --- |
| Response Type | Bandpass |
| Design Method | Chebyshev Type II |
| Filter Order | Minimum (84) |
| Match Exactly | Stopband |
| Fs | 100 Hz |
| Fstop1 | 0.01 Hz |
| Fpass1 | 0.05 Hz |
| Fpass2 | 9.8 Hz |
| Fstop2 | 10.1 Hz |
| Astop1 | 60 dB |
| Apass | 1 dB |
| Astop2 | 80 dB |

**Table 11.** Filter specifications for IIR VGRF filter.

**FIR VGRF Filter**

|  | **Specifications** |
| --- | --- |
| Response Type | Bandpass |
| Design Method | Equiripple |
| Filter Order | 361 |
| Density Factor | 20 |
| Fs | 100 Hz |
| Fstop1 | 0.0001 Hz |
| Fpass1 | 0.5 Hz |
| Fpass2 | 9.5001 Hz |
| Fstop2 | 10 |
| Astop1 | 30 |
| Apass | 0.1 |
| Astop2 | 30 |

**Table 12.** Filter specifications for FIR VGRF filter.

# RESULTS

## Part A

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**Figure 1.** Time-domain graph of the EEG and IIR filtered EEG signals.

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**Figure 2.** Magnitude spectrum of the DFT of the EEG and IIR filtered EEG signals.

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**Figure 3.** Phase spectrum of the DFT of the EEG and IIR filtered EEG signals.

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**Figure 4.** Zoomed in time-domain graph of the EEG and IIR filtered EEG signals to highlight the time delay between the original and filtered signals.

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**Figure 5.** Time-domain graph of the EEG and FIR filtered EEG signals.

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**Figure 6.** Magnitude spectrum of the DFT of the EEG and FIR filtered EEG signals.

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**Figure 7.** Phase spectrum of the DFT of the EEG and FIR filtered EEG signals.

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**Figure 8.** Zoomed in time-domain graph of the EEG and FIR filtered EEG signals to highlight the time delay between the original and filtered signals.

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**Figure 8.** Zoomed in time-domain graph of the EEG and appropriately shifted FIR filtered EEG signals to highlight the time delay between the original and filtered signals.

## Part B

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**Figure 9.** Time Domain of the original VGRF signal and the IIR filtered VGRF signal

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**Figure 10.** Magnitude Spectrum of the original VGRF signal and the IIR filtered VGRF signal

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**Figure 11.** Phase Spectrum of the original VGRF signal and the IIR filtered VGRF signal

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**Figure 12.** Zoomed in to highlight the time Delay of the original VGRF signal and the IIR filtered VGRF signal

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**Figure 13.** Time Domain of the original VGRF signal and the VIR filtered VGRF signal

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**Figure 14.** Magnitude Spectrum of the original VGRF signal and the VIR filtered VGRF signal

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**Figure 15.** Phase Spectrum of the original VGRF signal and the VIR filtered VGRF signal

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**Figure 16.** Zoomed in to highlight the time Delay of the original VGRF signal and the VIR filtered VGRF signal

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**Figure 17.** Corrected Time Delay of the original VGRF signal and the VIR filtered VGRF signal

# DISCUSSION

## Part A.

**A. What exact filter type and parameter values did you use for each of the 4 filters?**

Table 5 highlights the parameters used to design the IIR notch filter used on the EEG signal. Table 6 highlights the parameters used to design the FIR notch filter used on the EEG signal.

**B. What were the design criteria that guided your choice of the exact filter type and parameters for each of the 4 filters? Include plots of the magnitude and phase response of each filter and explain how the magnitude and phase response achieve your design criteria.**

The filters used on the EEG signal were designed with the goal of removing the 50 Hz AC noise while preserving the magnitude and phase of everything else.

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**Figure 18.** Graphs of the magnitude and phase response and the group delay of the IIR filter for the EEG signal

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**Figure 19.** Graphs of the magnitude and phase response and the group delay of the FIR filter for the EEG signal

Both the IIR and FIR magnitude responses show that the goal of removing the 50 Hz AC noise while preserving the magnitude of the other frequencies was achieved. This can be seen as there is -60 dB of attenuation at 50 Hz and approximately 0 dB of attenuation for all other frequencies. This means that the 50 Hz EEG component was heavily attenuated, making it negligible, while all the other frequency components were left unchanged.

The IIR phase response shows that the phase of all frequencies except at 50 Hz was maintained. The phase response is approximately 0 for all frequencies except for at 50 Hz where it becomes non-zero. This means that the phase at all frequency components is unchanged except for at 50 Hz which has an attenuated magnitude to remove its effect anyways. The group delay graph further supports this as the delay is 0 for all frequencies except 50 Hz.

The FIR phase response shows that the phase of all frequencies except at 50 Hz was maintained. The phase response is a linear result, so the filtered response becomes a time delayed result compared to the original EEG signal. Since the filtered signal is simply a time delayed version of the original, there is no phase distortion and the original phase is preserved. The group delay graph further supports this as the delay is 97 samples for all frequencies.

**C. How does a comparison of the corresponding input and output frequency spectra confirm that the 4 filters achieve the desired filtering of the two signals?**

As seen in Figures 2 and 3, the IIR filter achieves the goals of removing the 50 Hz AC noise and preserving the magnitude and phase of the other frequencies. Figure 2 shows that the magnitude spectrum of the IIR filtered and original EEG signal overlap at all frequencies except for those at 50 Hz. Figure 3 demonstrates that the phase spectrum overlaps at all the frequencies with some discrepancies around 50 Hz. The lack of a spike at 50 Hz on the filtered signal where the original one, signifies that the 50 Hz noise has been removed. Overlapping spectrums everywhere else show that the magnitude as phase is being preserved.

**D. What are the main differences that you observe from the output time-domain signals and frequency spectra between the IIR and FIR that you designed for each signal?**

From a zoomed-in comparison of the time-domain results, a time-delay can be seen on the FIR filter where the IIR filter does not have one. Figures 4, 8, and 9 best demonstrate this. Figure 4 shows that the IIR filter does not have a time delay, Figure 8 shows that the FIR filter does have a time delay, and Figure 9 shows how the time delay of the FIR filter can be corrected for by an appropriate time shift.

Analysis of the magnitude spectra reveals that the FIR filter has a larger range of frequencies around 50 Hz where the signal is attenuated. This can be seen on Figures 2 and 6. Analysis of the phase spectra reveals that the FIR filter has worse phase distortion compared to the IIR filter. Figures 3 and 7 demonstrate this as less overlap can be seen on Figure 7 than in Figure 3. The differences in the magnitude spectra can be explained by the wider transition bands in the FIR filter.

## Part B.

**A. What exact filter type and parameter values did you use for each of the 4 filters?**

Table 10 highlights the parameters used to design the IIR notch filter used on the VGRF signal. Table 11 highlights the parameters used to design the FIR notch filter used on the VGRF signal.

**B. What were the design criteria that guided your choice of the exact filter type and parameters for each of the 4 filters? Include plots of the magnitude and phase response of each filter and explain how the magnitude and phase response achieve your design criteria.**

The designs of the IIR and FIR filters for part 2 are to keep the harmonics for any frequency that is lower than 10 Hz while rejecting all signals above 10 Hz.

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**Figure 20.** Graphs of the magnitude and phase response and the group delay of the IIR filter for the VGRF signal

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**Figure 21.** Graphs of the magnitude and phase response and the group delay of the FIR filter for the VGRF signal

From the magnitude spectrum from both of the filters, we can see that the filters remove the signals that are greater than 10 Hz from the original signal. The IIR filter applies a -80 dB attenuation to the signals beyond 10 Hz, and the VIR filter applies a -30 dB attenuation to the signals above 10 Hz. By doing so, it makes the signals above 10 Hz negligible which successfully achieves rejecting the values above 10 Hz while keeping the harmonics below 10 Hz. We can also spot attenuation at 0 Hz on the magnitude spectrum, which contributes to the removal of DC constant component.

The phase spectrums, although has ripples caused by attempting to have a steeper transition band, are somewhat preserved for values less than 10 Hz. The phase response is linear, but the VIR-filtered response becomes a time-delayed result compared to the original VGRF signal. Since the VIR-filtered signal is simply a time-delayed version of the original, there is no phase distortion and the original phase is preserved. The IRR-filtered signal, on the other hand, is not affected at all since there are no time delays. The group delay graph further supports this as the delay is 0 for all frequencies below 10 Hz for the IIR and a group delay of around 180 for VIR.

**C. How does a comparison of the corresponding input and output frequency spectra confirm that the 4 filters achieve the desired filtering of the two signals?**

As seen in Figures 11 and 12, the IIR filter achieves the goals of removing the DC and signal noise above 10 Hz, while preserving the magnitude and phase of the other frequencies. Figure 11 shows that the magnitude spectrum of the IIR filtered and original FGRF signal are similarly aligned before getting over 10 Hz. Figure 12 demonstrates that the phase spectrum overlaps at most of the frequencies before over 10 Hz. Overall, it is easy to spot that there are some drastic changes to the signals beyond 10 Hz, therefore, the two filters achieved the desired filtering of VGRF.

**D. What are the main differences that you observe from the output time-domain signals and frequency spectra between the IIR and FIR that you designed for each signal?**

The advantages and disadvantages of FIR and IIR filters differ. FIR filters, in particular, have linear phase responses but wider transition bands, whereas IIR filters have non-linear phase responses but steeper transition bands.

The IIR filter has a more defined cut-off frequency. Because of their steep transition bands for low filter orders, our signal has a sharper cut-off frequency. However, this comes at the cost of non-linear phase responses, which affect the time difference between the individual's steps. This is visible at 10 Hz, where the IIR spectrum is significantly reduced in comparison to the FIR signal. However, the magnitude spectrum of the FIR filter is more rounded and less extreme, possibly due to better noise filtering without sacrificing linear phase delay. Furthermore, a sharper transition results in a longer delay in the phase spectrums.

When compared to the IIR filter, the FIR filter produces a much more accurate signal in the time domain. Much higher order is required in FIR filters to achieve a steep transition band. A higher order would result in a longer time delay, but for our purposes of analyzing gait, this would have no effect on our data analysis. Furthermore, although there is a constant shift in time in the FIR-filtered signal, the amplitudes are largely maintained. The IIR filter, on the other hand, causes the output signal to deviate from its original amplitude.

# CONCLUSION

We successfully analyzed the effects that different filters can do on the VGRF and EEG signals using MATLAB 2022b. We understood the trade-offs using different tools in MATLAB for the two signals.