IBEHS 3A03 Assignment #3:

Fourier Analysis of Biomedical Signals

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# PURPOSE

Based on our knowledge of Fourier analysis of discrete-time signals using the custom function *fourier\_dt( )*, we analyzed the frequency content of a blood-flow velocity (BFV) signal from doppler ultrasound and of electroencephalogram (EEG) signals. We also interpreted the results of spectral analysis.

# METHODOLOGY

## Part A: BFV Analysis

### Task A1) Magnitude Spectrum of Entire Signal BFVdu

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 BFVdu signal. The magnitude spectrum was then plotted. Table 1 describes the variables used for this task.

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

| **Variable** | **Assignment / Location Used** | **Description** |
| --- | --- | --- |
| BVFdu | load BFVdata\_assignment3.mat | Time domain blood flow velocity signal |
| Fs | load BFVdata\_assignment3.mat  Fs = 100 | Sampling rate |
| mBFV | [mBFV, phBFV, fBFV] = fourier\_dt(BFVdu, Fs, 'full'); | Magnitude Spectrum of the entire BFVdu signal |
| phBFV | [mBFV, phBFV, fBFV] = fourier\_dt(BFVdu, Fs, 'full'); | Phases Spectrum of the entire BFVdu signal |
| fBFV | [mBFV, phBFV, fBFV] = fourier\_dt(BFVdu, Fs, 'full'); | Frequency of the entire BFVdu signal |

### Task A2) Magnitude Spectrum from element 1 to L

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 BFVdu signal and shortened segments of the BFVdu signal. The segment lengths were specified by the variable L. The produced magnitude spectrums were plotted and compared in order to find the smallest segment of BFVdu that still showed the harmonic structure of the full BFVdu signal. Table 2 describes the variables used for this task.

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

| **Variable** | **Assignment / Location Used** | **Description** |
| --- | --- | --- |
| BVFdu | load BFVdata\_assignment3.mat | Time domain blood flow velocity signal |
| Fs | load BFVdata\_assignment3.mat  Fs = 100 | Sampling rate |
| mFullBFV | [mFullBFV, phFullBFV, fFullBFV] = fourier\_dt(BFVdu, Fs, 'full'); | Magnitude Spectrum of the entire BFVdu signal |
| phFullBFV | [mFullBFV, phFullBFV, fFullBFV] = fourier\_dt(BFVdu, Fs, 'full'); | Phases Spectrum of the entire BFVdu signal |
| fFullBFV | [mFullBFV, phFullBFV, fFullBFV] = fourier\_dt(BFVdu, Fs, 'full'); | Frequency of the entire BFVdu signal |
| L | L = 400, 300, 200 | Controls length of shorted signal |
| adj\_BFVdu | adj\_BFVdu = BFVdu(1:L) | A portion of the BFVdu signal up to L |
| m400BFV | [m400BFV, ph400BFV, f400BFV] = fourier\_dt(adj\_BFVdu, Fs, 'full'); | Magnitude Spectrum of the BFVdu signal up to L = 400 |
| ph400BFV | [m400BFV, ph400BFV, f400BFV] = fourier\_dt(adj\_BFVdu, Fs, 'full'); | Phase Spectrum of the BFVdu signal up to L = 400 |
| f400BFV | [m400BFV, ph400BFV, f400BFV] = fourier\_dt(adj\_BFVdu, Fs, 'full'); | Frequency of the BFVdu signal up to L = 400 |
| m300BFV | [m300BFV, ph300BFV, f300BFV] = fourier\_dt(adj\_BFVdu, Fs, 'full'); | Magnitude Spectrum of the BFVdu signal up to L = 300 |
| ph300BFV | [m300BFV, ph300BFV, f300BFV] = fourier\_dt(adj\_BFVdu, Fs, 'full'); | Phase Spectrum of the BFVdu signal up to L = 300 |
| f300BFV | [m300BFV, ph300BFV, f300BFV] = fourier\_dt(adj\_BFVdu, Fs, 'full'); | Frequency of the BFVdu signal up to L = 300 |
| m200BFV | [m200BFV, ph200BFV, f200BFV] = fourier\_dt(adj\_BFVdu, Fs, 'full'); | Magnitude Spectrum of the BFVdu signal up to L = 200 |
| ph200BFV | [m200BFV, ph200BFV, f200BFV] = fourier\_dt(adj\_BFVdu, Fs, 'full'); | Phase Spectrum of the BFVdu signal up to L = 200 |
| f200BFV | [m200BFV, ph200BFV, f200BFV] = fourier\_dt(adj\_BFVdu, Fs, 'full'); | Frequency of the BFVdu signal up to L = 200 |

### Task A3) Magnitude Spectrum up to sample L with Zero-Padding

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 BFVdu signal and shortened segments of the BFVdu signal. The segment lengths were specified by the variable L and were then zero-padded to create an input of length 2L. The produced magnitude spectrums were plotted and compared in order to determine the effects of zero-padding. Table 3 describes the variables used for this task.

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

| **Variable** | **Assignment / Location Used** | **Description** |
| --- | --- | --- |
| BVFdu | load BFVdata\_assignment3.mat | Time domain blood flow velocity signal |
| Fs | load BFVdata\_assignment3.mat  Fs = 100 | Sampling rate |
| BFVdu | [mFullBFV, phFullBFV, fFullBFV] = fourier\_dt(BFVdu, Fs, 'full'); | time-domain BFV signal |
| mFullBFV | Magnitude Spectrum of the entire BFVdu signal |
| phFullBFV | Phases Spectrum of the entire BFVdu signal |
| fFullBFV | Frequency of the entire BFVdu signal |
| L | L = 400, 300, 200 | A shortened length |
| adj\_BFVdu | adj\_BFVdu = BFVdu(1:L) | A portion of the BFVdu signal up to L |
| zeropadding | zeropadding = [adj\_BFVdu; zeros(L,1)]; | A list of zero of size L appended to the end of a portion of BFVdu signal of length L |
| m400zeroBFV | [m400zeroBFV, ph400zeroBFV, f400zeroBFV] = fourier\_dt(zeropadding, Fs, 'full'); | Magnitude Spectrum of the BFVdu signal up to L = 400 with zero padding of length L |
| ph400zeroBFV | Phase Spectrum of the BFVdu signal up to L = 400 with zero padding of length L |
| f400zeroBFV | Frequency of the BFVdu signal up to L = 400 with zero padding of length L |
| m300zeroBFV | [m300zeroBFV, ph300zeroBFV, f300zeroBFV] = fourier\_dt(zeropadding, Fs, 'full'); | Magnitude Spectrum of the BFVdu signal up to L = 300 with zero padding of length L |
| ph300zeroBFV | Phase Spectrum of the BFVdu signal up to L = 300 with zero padding of length L |
| f300zeroBFV | Frequency of the BFVdu signal up to L = 300 with zero padding of length L |
| m200zeroBFV | [m200zeroBFV, ph200zeroBFV, f200zeroBFV] = fourier\_dt(zeropadding, Fs, 'full'); | Magnitude Spectrum of the BFVdu signal up to L = 200 with zero padding of length L |
| ph200zeroBFV | Phase Spectrum of the BFVdu signal up to L = 200 with zero padding of length L |
| f200zeroBFV | Frequency of the BFVdu signal up to L = 200 with zero padding of length L |

## Part B: EEG Analysis

### Task B1) Magnitude Spectrum of EEG Time-Domain Signals

The custom function, fourier\_dt(), was used to produce the magnitude spectrum, phase spectrum, and the frequencies of the discrete fourier transform of the given EEG signals. The magnitude and phase spectrums were then plotted. Table 4 describes the variables used for this task.

**Table 4.** Assignments used in Task B1 in order of implementation.

| **Variable** | **Assignment / Location Used** | **Description** |
| --- | --- | --- |
| Fs | Fs = 500 | sampling frequency |
| EEG1 | [mEEG1, phEEG1, fEEG1] = fourier\_dt(EEG1,Fs,'full') | EEG1 time-domain signal |
| mEEG1 | magnitude spectrum of EEG1 |
| phEEG1 | phases spectrum of EEG1 |
| fEEG1 | array of scaled frequencies of EEG1 |
| EEG2 | [mEEG2, phEEG2, fEEG2] = fourier\_dt(EEG2,Fs,'full') | EEG2 time-domain signal |
| mEEG2 | magnitude spectrum of EEG2 |
| phEEG2 | phases spectrum of EEG2 |
| fEEG2 | array of scaled frequences of EEG2 |

### Task B2) Band Power and Normalized Band Power

The custom function, *fourier\_dt()*, was used to produce the magnitude spectrum, phase spectrum, and the frequencies of the discrete fourier transform of the given EEG signals. The produced frequencies and corresponding magnitudes were then divided into sub-arrays that hold the frequencies and magnitudes associated with different states of consciousness (see Table 6). Band power for each of these sub-arrays was calculated by summing each element of the array squared with itself. Normalized band power was calculated by dividing each element of the band power arrays by the bandwidth of the sub-array. The band power and normalized band power was then plotted as histograms. Table 5 describes the variables used for this task.

**Table 5.** Variables used in Task B2 in order of implementation.

| **Variable** | **Assignment / Location Used** | **Description** |
| --- | --- | --- |
| d\_LB | d\_LB = 0 | Lower-bound (LB) of delta rhythm/wave frequency band range (FBR) |
| d\_UB | d\_UB = 3 | Upper-bound (UB) of delta rhythm/wave FBR |
| t\_LB | t\_LB = 3 | LB of theta rhythm/wave FBR |
| t\_UB | t\_UB = 8 | UB of theta rhythm/wave FBR |
| a\_LB | a\_LB = 8 | LB of alpha rhythm/wave FBR |
| a\_UB | a\_UB = 13 | UB of alpha rhythm/wave FBR |
| b\_LB | b\_LB = 13 | LB of beta rhythm/wave FBR |
| b\_UB | b\_UB = 25 | UB of beta rhythm/wave FBR |
| g\_LB | g\_LB = 25 | LB of gamma rhythm/wave FBR |
| g\_UB | g\_UB = 100 | UB of gamma rhythm/wave FBR |
| FBR\_d\_1 | FBR\_d\_1 = find(fEEG1 >= d\_LB & fEEG1 < d\_UB) | delta FBR for EEG1 |
| FBR\_t\_1 | FBR\_t\_1 = find(fEEG1 >= t\_LB & fEEG1 < t\_UB) | theta FBR for EEG1 |
| FBR\_a\_1 | FBR\_a\_1 = find(fEEG1 >= a\_LB & fEEG1 < a\_UB) | alpha FBR for EEG1 |
| FBR\_b\_1 | FBR\_b\_1 = find(fEEG1 >= b\_LB & fEEG1 < b\_UB) | beta FBR for EEG1 |
| FBR\_g\_1 | FBR\_g\_1 = find(fEEG1 >= g\_LB & fEEG1 <= g\_UB) | gamma FBR for EEG1 |
| FBR\_d\_2 | FBR\_d\_2 = find(fEEG2 >= d\_LB & fEEG2 < d\_UB) | delta FBR for EEG2 |
| FBR\_t\_2 | FBR\_t\_2 = find(fEEG2 >= t\_LB & fEEG2 < t\_UB) | theta FBR for EEG2 |
| FBR\_a\_2 | FBR\_a\_2 = find(fEEG2 >= a\_LB & fEEG2 < a\_UB) | alpha FBR for EEG2 |
| FBR\_b\_2 | FBR\_b\_2 = find(fEEG2 >= b\_LB & fEEG2 < b\_UB) | beta FBR for EEG2 |
| FBR\_g\_2 | FBR\_g\_2 = find(fEEG2 >= g\_LB & fEEG2 <= g\_UB) | gamma FBR for EEG2 |
| BP\_d\_1 | BP\_d\_1 = sum((mEEG1(FBR\_d\_1(1:end))).^2) | Delta band power (BP) of EEG1 |
| BP\_t\_1 | BP\_t\_1 = sum((mEEG1(FBR\_t\_1(1:end))).^2) | Theta BP of EEG1 |
| BP\_a\_1 | BP\_a\_1 = sum((mEEG1(FBR\_a\_1(1:end))).^2) | Alpha BP of EEG1 |
| BP\_b\_1 | BP\_b\_1 = sum((mEEG1(FBR\_b\_1(1:end))).^2) | Beta BP of EEG1 |
| BP\_g\_1 | BP\_g\_1 = sum((mEEG1(FBR\_g\_1(1:end))).^2) | Gamma BP of EEG1 |
| BPs\_1 | BPs\_1 = [BP\_d\_1 BP\_t\_1 BP\_a\_1 BP\_b\_1 BP\_g\_1] | array of BPs of EEG1 |
| rhythms | rhythms = {'Delta [0,3)' 'Theta [3,8)' 'Alpha [8,13)' 'Beta [13,25)' 'Gamma [25,100]'} | x-axis used to describe frequency band ranges (in Hz) categorized by rhythm/wave |
| normBP\_d\_1 | normBP\_d\_1 = BP\_d\_1/(d\_UB - d\_LB) | Delta normalized BP (normBP) of EEG1 |
| normBP\_t\_1 | normBP\_t\_1 = BP\_t\_1/(t\_UB - t\_LB) | Theta normBP of EEG1 |
| normBP\_a\_1 | normBP\_a\_1 = BP\_a\_1/(a\_UB - a\_LB) | Alpha normBP of EEG1 |
| normBP\_b\_1 | normBP\_b\_1 = BP\_b\_1/(b\_UB - b\_LB) | Beta normBP of EEG1 |
| normBP\_g\_1 | normBP\_g\_1 = BP\_g\_1/(g\_UB - g\_LB) | Gamma normBP of EEG1 |
| normBPs\_1 | normBPs\_1 = [normBP\_d\_1 normBP\_t\_1 normBP\_a\_1 normBP\_b\_1 normBP\_g\_1] | array of normalized BPs of EEG1 |
| BP\_d\_2 | BP\_d\_2 = sum((mEEG2(FBR\_d\_2(1:end))).^2) | Delta BP of EEG2 |
| BP\_t\_2 | BP\_t\_2 = sum((mEEG2(FBR\_t\_2(1:end))).^2) | Theta BP of EEG2 |
| BP\_a\_2 | BP\_a\_2 = sum((mEEG2(FBR\_a\_2(1:end))).^2) | Alpha BP of EEG2 |
| BP\_b\_2 | BP\_b\_2 = sum((mEEG2(FBR\_b\_2(1:end))).^2) | Beta BP of EEG2 |
| BP\_g\_2 | BP\_g\_2 = sum((mEEG2(FBR\_g\_2(1:end))).^2) | Gamma BP of EEG2 |
| BPs\_2 | BPs\_2 = [BP\_d\_2 BP\_t\_2 BP\_a\_2 BP\_b\_2 BP\_g\_2] | array of BPs of EEG2 |
| normBP\_d\_2 | normBP\_d\_2 = BP\_d\_2/(d\_UB - d\_LB) | Delta normBP of EEG2 |
| normBP\_t\_2 | normBP\_t\_2 = BP\_t\_2/(t\_UB - t\_LB) | Theta normBP of EEG2 |
| normBP\_a\_2 | normBP\_a\_2 = BP\_a\_2/(a\_UB - a\_LB) | Alpha normBP of EEG2 |
| normBP\_b\_2 | normBP\_b\_2 = BP\_b\_2/(b\_UB - b\_LB) | Beta normBP of EEG2 |
| normBP\_g\_2 | normBP\_g\_2 = BP\_g\_2/(g\_UB - g\_LB) | Gamma normBP of EEG2 |
| normBPs\_2 | normBPs\_2 = [normBP\_d\_2 normBP\_t\_2 normBP\_a\_2 normBP\_b\_2 normBP\_g\_2] | array of normalized BPs of EEG2 |

**Table 6.** Adapted from Lecture 22, Fourier analysis of biomedical signals.

| **Rhythm/Wave** | **Prominent Brain State(s)** |
| --- | --- |
| Alpha | Awake & relaxed with eyes closed |
| Beta | Awake activity AND deep NREM sleep |
| Theta | Light NREM sleep |
| Delta | Deep NREM sleep |
| Gamma | Sensory processing and binding |

## BONUS: Using spectrogram( ) on BFV and EEG Data

Spectrograms of the BFVdu and EEG signals were plotted based on lengths of windowed segments, number of samples overlapping per window position and number of discrete Discrete Fourier Transform (DFT) points. These variables were defined based on producing visually distinct spectrograms to yield appropriate analyses. Table 7 describes the variables used in this task.

**Table 7.** Variables used in BONUS in order of implementation.

| **File** | **Variable** | **Assignment** | **Description** |
| --- | --- | --- | --- |
| PART A | Fs | Fs = 100 | sampling frequency |
| winlen | winlen = 60 | the desired length of windowed segments |
| overlap | overlap = 10 | the desired samples overlapping per window position |
| NFFT | NFFT = 400 | signal is zero-padded to this length; number of DFT points |
| BFVdu | [s\_BFVdu,f\_BFVdu,t\_BFVdu] = spectrogram(BFVdu,winlen,overlap,NFFT,Fs) | BFVdu time-domain signal |
| s\_BFVdu | short-time Fourier transform of BFVdu |
| f\_BFVdu | frequency of BFVdu |
| t\_BFVdu | time instants of BFVdu |
| cb1 | cb1 = colorbar; | displays a vertical colorbar to the right of the current axes or chart |
| PART B | windowLength | windowLength = 1e3 | the desired length of windowed segments |
| sampleOverlap | sampleOverlap = 5e2 | the desired samples overlapping per window position |
| NFFT | NFFT = 2e4 | signal is zero-padded to this length; number of DFT points |
| EEG1 | [s\_EEG1, f\_EEG1, t\_EEG1] = spectrogram(EEG1,winlen,overlap,NFFT,Fs) | EEG1 time-domain signal |
| s\_EEG1 | short-time Fourier transform of EEG1 |
| f\_EEG1 | frequency of EEG1 |
| t\_EEG1 | time instants of EEG1 |
| Fs | Fs = 500 | sampling frequency; **assumed that this can’t be changed** |
| cb2 | cb2 = colorbar | displays a vertical colorbar to the right of the current axes or chart |
| EEG2 | [s\_EEG2, f\_EEG2, t\_EEG2] = spectrogram(EEG2,winlen,overlap,NFFT,Fs) | EEG2 time-domain signal |
| s\_EEG2 | short-time Fourier transform of EEG2 |
| f\_EEG2 | frequency of EEG2 |
| t\_EEG2 | time instants of EEG2 |

# RESULTS

## Part A

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**Figure 1.** Magnitude spectrum of the entire BFVdu signal.

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**Figure 2.** The magnitude spectrum of a portion of signal BFVdu starting at element 1 in the array and going up to element L = 400.

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| --- |

**Figure 3.** The magnitude spectrum of a portion of signal BFVdu starting at element 1 in the array and going up to element L = 300.

|  |
| --- |

**Figure 4.** The magnitude spectrum of a portion of signal BFVdu starting at element 1 in the array and going up to element L = 200.

|  |
| --- |

**Figure 5.** The magnitude spectrum of the signal portion up to L = 400 with zero-padding of length L = 400.

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| --- |

**Figure 6.** The magnitude spectrum of the signal portion up to L = 300 with zero-padding of length L = 300.

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**Figure 7.** The magnitude spectrum of the signal portion up to L = 200 with zero-padding of length L = 200.

Figures 2–4 demonstrate the magnitude spectra of a portion of the BFVdu signal from element 1 of the array to an L value that we determined. With the objective of finding the smallest value of L for which the harmonic structure is well represented in the signal segment, we tried L = 200, 300 and 400. We found that at L = 300, the harmonic structure is still present, while at L = 200, it does not seem so. Therefore, we determined that L = 300 is the lowest value of L for which the harmonic structure can still be observed.

Figures 5–7 represent the magnitude spectra of the signal portions up to sample L with zero-padding of length L. Zero-padding helps to add more detail to the Fourier transform by increasing the amount of frequencies the signal is analyzed at. In this case, zero-padding created several peaks and troughs to match the smaller, not associated with the harmonic structure, peaks and troughs of the full signal. However, these newly created peaks and troughs did not match the amplitude of the full signal. This made determining the harmonic structure more difficult for the zero-padded inputs.

## Part B

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**Figure 8.** Magnitude spectrum of EEG1 as a graph of X(f) (in µV) versus f (in Hz).

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**Figure 9.** Magnitude spectrum of EEG2 as a graph of X(f) (in µV) versus f (in Hz).

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| --- |

**Figure 10.** Band power (in µV2) of EEG1 categorized by rhythm/wave (delta, theta, alpha, beta, gamma) frequency band ranges (in Hz).

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**Figure 11.** Normalized band power (in µV2/Hz) of EEG1 categorized by rhythm/wave (delta, theta, alpha, beta, gamma) frequency band ranges (in Hz).

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| --- |

**Figure 12.** Band power (in µV2) of EEG2 categorized by rhythm/wave (delta, theta, alpha, beta, gamma) frequency band ranges (in Hz).

|  |
| --- |

**Figure 13.** Normalized band power (in µV2/Hz) of EEG2 categorized by rhythm/wave (delta, theta, alpha, beta, gamma) frequency band ranges (in Hz).

Figures 8 and 9 depict the magnitude spectra of EEG1 and EEG2 signals, respectively. Figures 10 and 12 depict the band power of each signal, with corresponding normalized band powers shown in Figures 11 and 13. Band powers were categorized by rhythm/wave frequency band ranges (delta, theta, alpha, beta, gamma) in Hz. To determine which EEG signal was awake & resting with eyes closed versus in deep NREM sleep, we referred to the definitions of these states that are described in Table 6 which is an adaptation from Lecture 22. As shown in Figures 10–13, EEG2 has *proportionally* more prominent alpha wave band power than EEG1, relative to other frequency band ranges. Alpha waves have a prominent brain state of awakeness & relaxation with eyes closed. As well, EEG2 depicts a significantly lower delta wave band power than EEG1. Delta waves have a prominent brain state of deep NREM sleep.

Therefore, EEG2 was recorded from an awake & relaxed subject with their eyes closed, while EEG1 was recorded from a subject in deep NREM sleep. We also concluded that delta wave power recorded in the EEG2 signal was likely from low frequency recording noise.

## Bonus

### Part A)

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**Figure 14.** Spectrograms of the BFV signal.

### Part B)

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**Figure 15.** Spectrograms of EEG1 (top) and EEG2 (bottom) signals.

Figure 14 depicts the spectrogram of the BFVdu signal which appears to peak near 0 Hz (yellow colours). As the frequency increases, the colour gradually becomes more blue. Like the magnitude spectrum from earlier, the blood flow velocity would fluctuate and gradually decrease with the increase of frequency. Eventually, it approaches 0 m/s around 7 Hz. This is accurately depicted in the spectrogram of the BFV graph. The spectrogram also shows that the blood flow velocity signal was relatively stable as the frequency content of the magnitude spectrum did not change too much over time.

Figure 15 depicts spectrograms of EEG1 and EEG2. Both signals appear to have high magnitudes of X(f), based on the yellow and green colours, near 0 Hz which corresponds to delta rhythm/wave frequency band ranges. Over time, |X(f)| fluctuates near 0 Hz (observed by the fluctuating green and yellow colouring) which is possibly indicative of signal intensification from low-frequency recording noise. This is supported by the lack of fluctuation when f ≥ 3 Hz (beyond delta range). The spectrogram of EEG2 shows a consistent light blue band around 10 Hz, indicating a consistent magnitude of alpha rhythm/wave. On the contrary, the spectrogram of EEG1 lacks this observation. This further supports the notion that EEG2 was recorded by an awake & relaxed subject with their eyes closed, while EEG1 was recorded by a subject in deep NREM sleep.

# CONCLUSION

We successfully analyzed frequency content of a BFV signal and of EEG signals using MATLAB 2022a. We also used spectrogram( ) to compute and plot how the BFV and EEG amplitude spectra might change over time throughout the duration of the signals.