Giaan Nguyen

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Lab 02

ECE 3366: Intro to Digital Signal Processing

Introduction

The finite impulse response (FIR) filter is typically defined by a set of values defined for some finite duration, whereas the infinite impulse response (IIR) filter is defined by a difference equation. In this lab, the linear phase property is analyzed in the comparison of the two lowpass filters and applied to a pre-existing speech recording.

Procedures

With the recording from Male 1 in consideration, since the dominant spectral peaks for each of his four sound artifacts are centered around 150 [Hz], consider 150 [Hz] as the fundamental frequency. Before applying FIR and IIR lowpass filters separately to the recording, they are the frequency response of each filter at different orders (1, 2, 3, 4, 5, 10, 15, and 20) was observed. Both filters were then applied to a 150 [Hz] square wave – frequency based on Male 1 – at a duration of 0.1 seconds with a cutoff frequency of three times the fundamental frequency (i.e., cutoff of 450 [Hz]), and comparisons were made for the first and fifth order filters.

The first and fifth order filters were then applied to each of the four sound artifacts from Male 1. The time plots and frequency response for the original and filtered signals were observed. Lastly, the original and filtered sounds were applied to filtfilt.m.

Results and Discussion

In Figure 1, the frequency response (both magnitude and phase) were plotted for all aforementioned orders of the FIR lowpass filter. It is important to note that freqz() is not efficient for analyzing multiple phase responses.

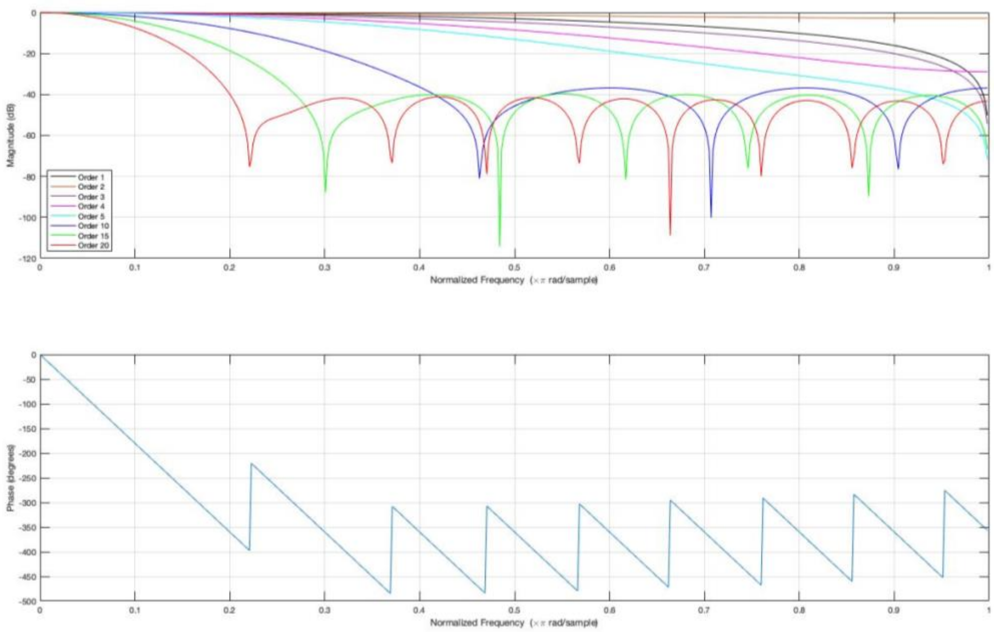

Figure 1. FIR lowpass frequency response of different orders. The magnitude (top) and phase (bottom) response of the FIR filter at orders 1,2,3,4,5,10,15, and 20 are depicted, with caution that the phase response only plots orders 10 and above.

Interestingly, when the order is less than 10 (and especially if the order is an odd integer), the magnitude response converge at a cutoff frequency of 1 $\left[\frac{\pi \cdot rad}{samp}\right]$, and – albeit not shown in Figure 1 due to the inefficiency of freqz() – the phase response is a linear function of slope $-450\ \left[\frac{deg}{\pi \cdot rad/samp}\right]$. (The phase response can be observed for orders 1-5 by changing the index in the provided code.) When the order is 10 or above, the cutoff frequency decreases as the order increases, with the magnitude response for each of the three orders having a sinc behavior; the phase response of the three orders also show a linear response, albeit a piecewise linear function.

The square wave is set at 150 [Hz] to emulate the fundamental frequency of Male 1. Figure 2 depicts the original square wave as well as the FIR-filtered square waves at different orders.

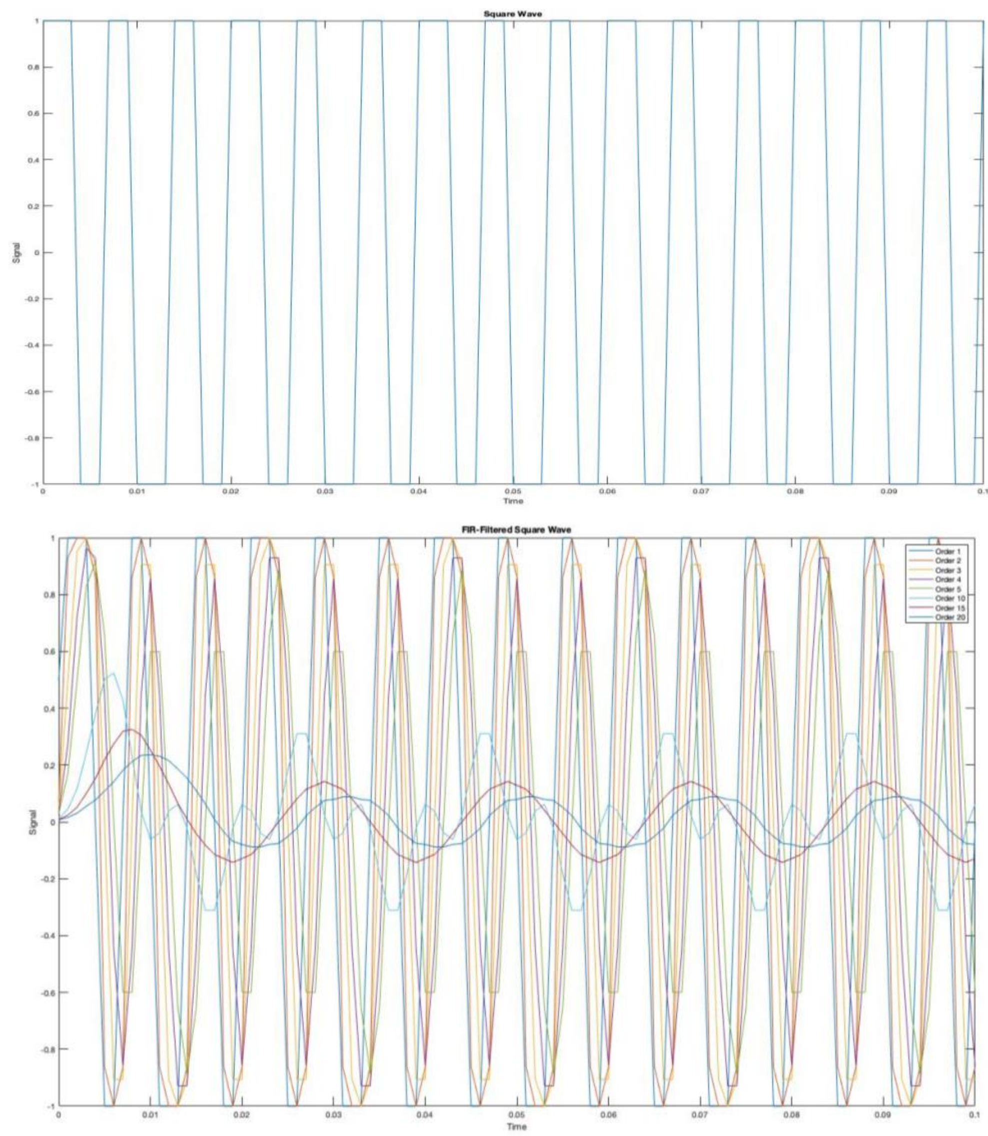

Figure 2. FIR-filtered square wave. The original square wave (top) and the FIR-filtered square wave at different orders (bottom) are depicted.

For FIR filter orders 1-5, the amplitude of the square wave decreases as the order increases, but overall most of the shape of the square wave is preserved. For orders 10 and above, the filtered wave becomes more sinusoidal as the order increases, and the period of the wave increases. This should make sense as the cutoff frequency for orders 10 and above decreased, as seen in Figure 1.

In Figure 3, the frequency response (both magnitude and phase) were plotted for all aforementioned orders of the IIR Butterworth filter. Again, freqz() is not efficient for analyzing multiple phase responses.

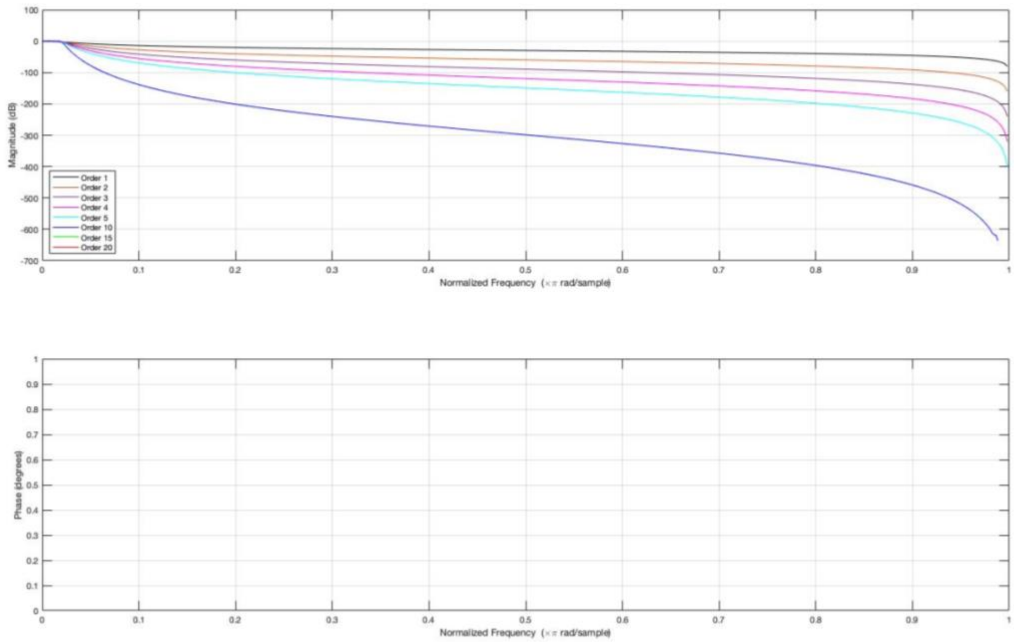

Figure 3. IIR lowpass frequency response of different orders. The magnitude (top) and phase (bottom) response of the IIR filter at orders 1,2,3,4,5,10,15, and 20 are depicted, with caution that the phase response only plots orders 10 and above.

From Figure 3, the IIR lowpass filter of only orders 1-10 are depicted in the magnitude response, with the magnitude response of each curve converging to a cutoff frequency of $1\ \left[\frac{\pi\cdot rad}{samp}\right]$. However, unlike the FIR, as the order increases, the IIR magnitude response becomes more curved at low frequencies. Although orders 15 and 20 are not shown, it can be inferred that they would most likely exhibit a steep curve at low frequencies. In addition, while freqz() is not best for analysis of phase response, the index can be restricted in the provided in the code to see that each phase response exhibits an exponential decay, with the rate of decay increasing as the order increases; again, it can be inferred that Figure 3 depicts orders 10, 15, and 20 since decay rates are increased to the extent that the quasi-linear portion becomes nearly vertical.

Figure 4 shows the IIR-filtered square wave set at different orders. Even from the first order filter, the shape of the square wave is lost, and the amplitude decreased to less than one-fifth of its original amplitude. As the order increases, the period of the wave increases, and the amplitude of the wave decreases to the extent that the wave nearly looks linear.

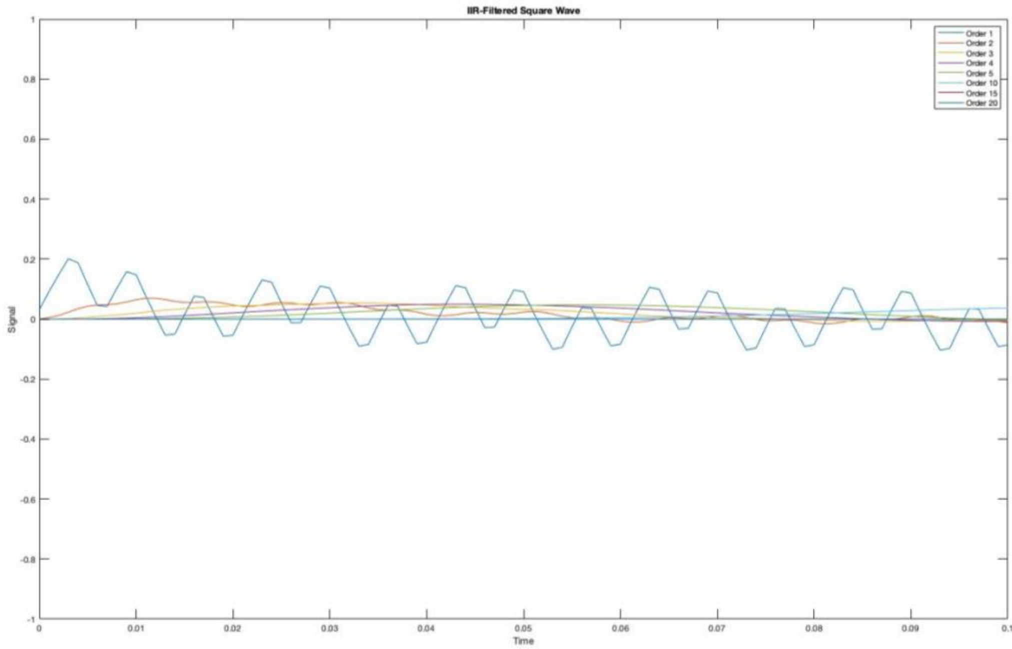

Figure 4. IIR-filtered square wave. The IIR-filtered square wave at different orders are depicted.

Figure 5 shows a comparison of the original square wave and both the FIR- and IIR-filtered waves for the first and fifth orders.

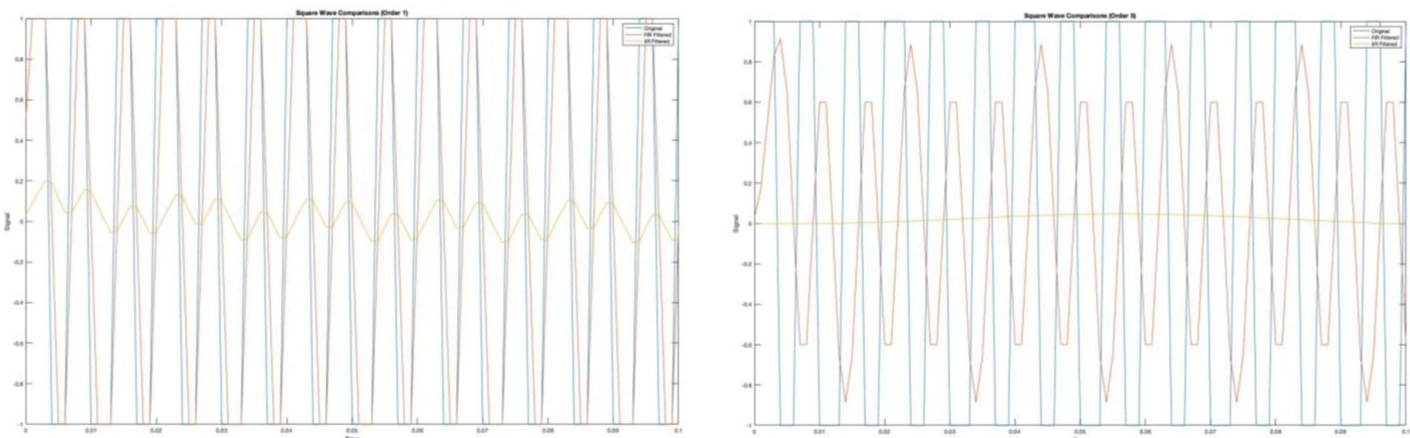

Figure 5. Comparison of square waves. The left image compares the first order filters, and the right image compares the fifth order filters. Blue waves are the original square waves, red are FIR-filtered, and yellow are IIR-filtered.

From the first order alone, we see that the FIR filter mostly preserves the shape of the original square wave, whereas the IIR filter has a dramatically decreased amplitude. From the fifth order, the FIR-filtered wave somewhat follows the shape of the square wave, whereas the IIR-filtered “wave” essentially becomes a line. Between the two filters, the FIR filter is the best at maintaining the square wave form, due to the linear phase property seen in the FIR phase response in comparison to the exponential behavior of the IIR. It can be observed that filters with linear phase response provide preservation of the waveform intended to be filtered.

Applying the first and fifth orders of both FIR and IIR filters to the Male 1 sound artifacts with cutoff frequency of 200 [Hz], Figures 6-9 depicts the resulting waveforms and amplitude spectra.

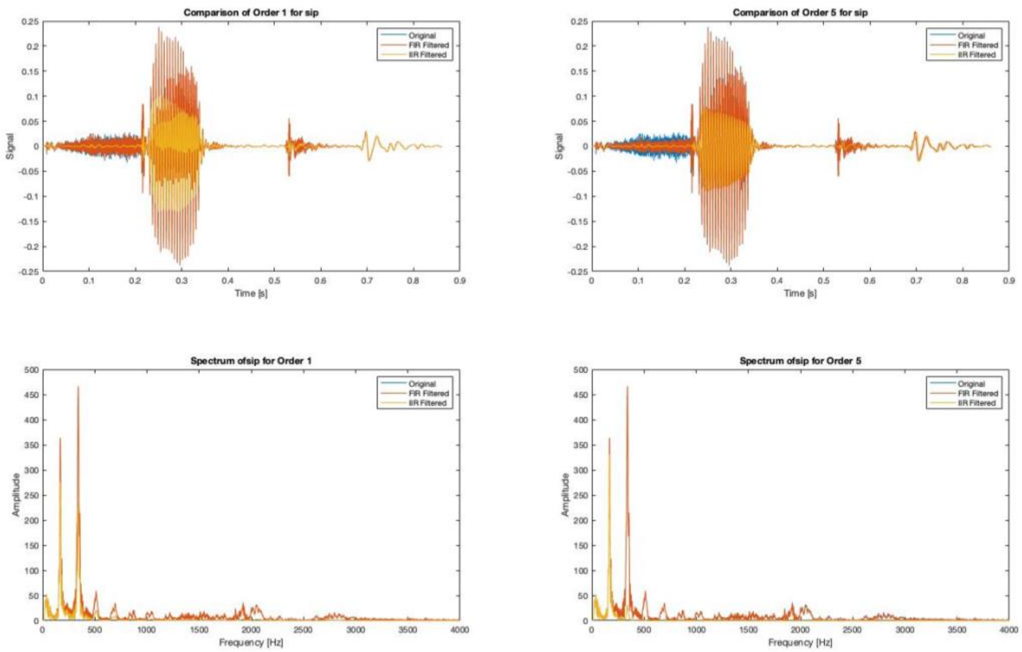

Figure 6. Waveform and spectrum of sip. The left side shows the waveform (top) and spectrum (bottom) for the original and filtered (of order 1) signals of "sip". Similarly, the right side shows that for the original and filtered (of order 5) signals.

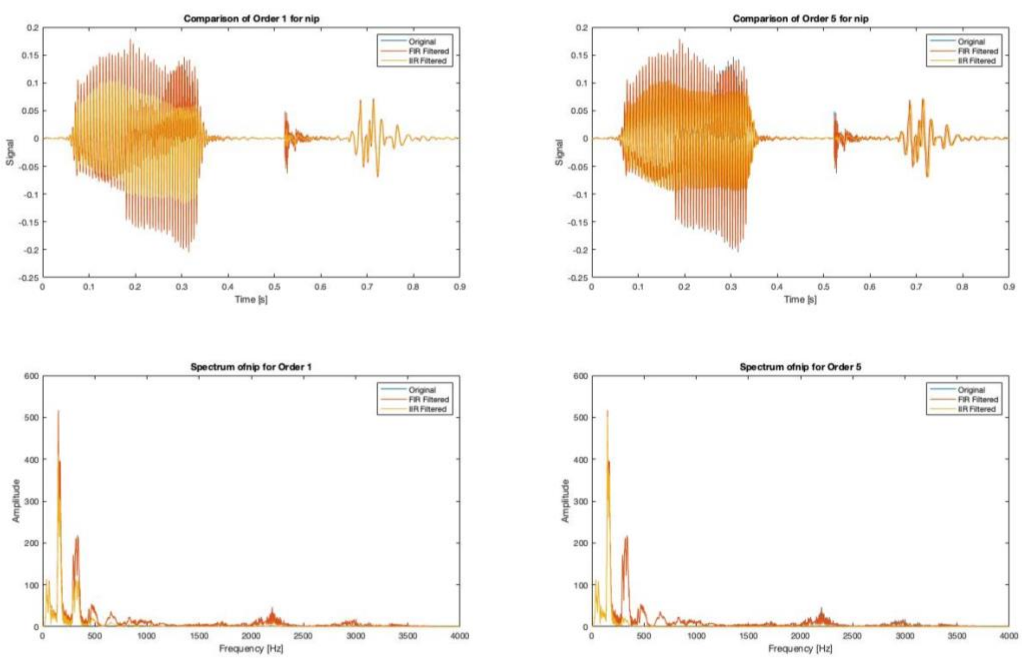

Figure 7. Waveform and spectrum of nip. The left side shows the waveform (top) and spectrum (bottom) for the original and filtered (of order 1) signals of "nip". Similarly, the right side shows that for the original and filtered (of order 5) signals.

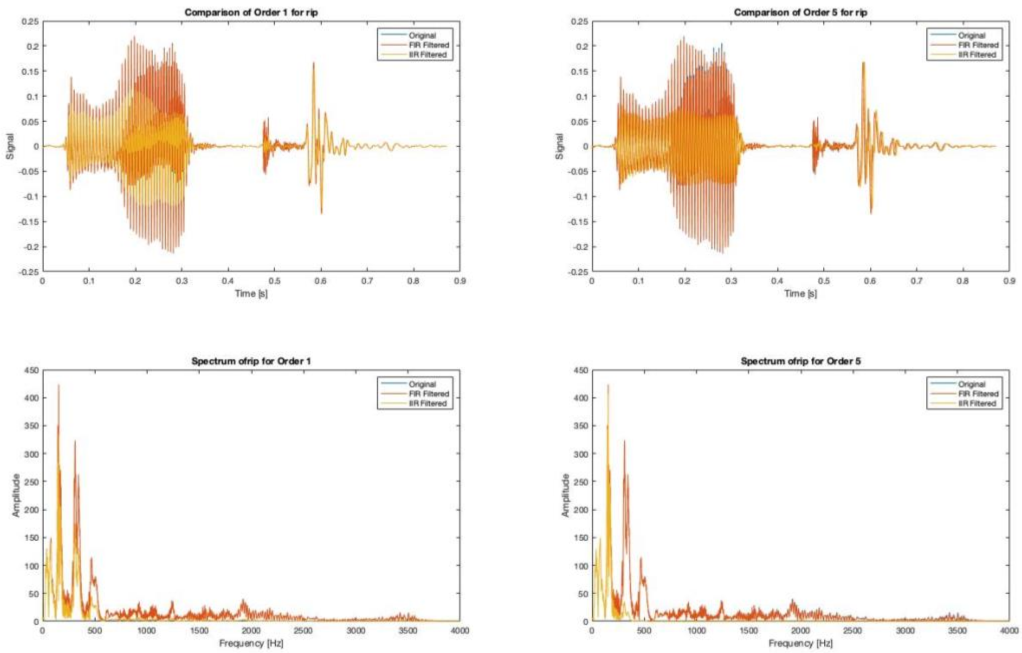

Figure 8. Waveform and spectrum of rip. The left side shows the waveform (top) and spectrum (bottom) for the original and filtered (of order 1) signals of “rip”. Similarly, the right side shows that for the original and filtered (of order 5) signals.

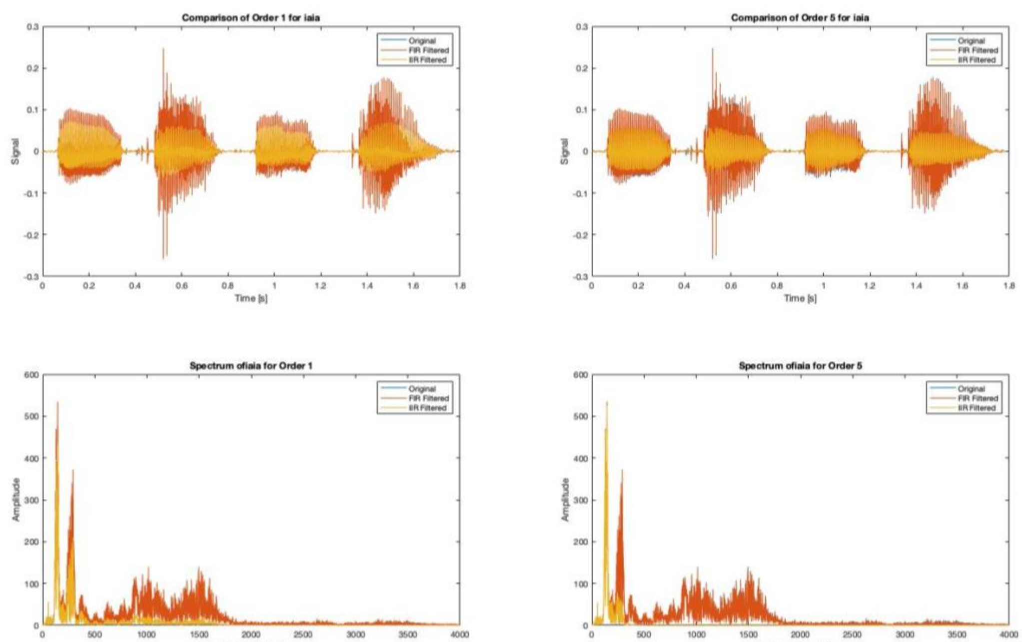

Figure 9. Waveform and spectrum of iaia. The left side shows the waveform (top) and spectrum (bottom) for the original and filtered (of order 1) signals of “iaia”. Similarly, the right side shows that for the original and filtered (of order 5) signals.

From Figures 6-9, we see that the FIR filters for both first and fifth orders are best at preserving the waveform (and consequently much of the frequency spectra) of the original sound artifacts. When listening to the signals, the IIR-filtered signal becomes muffled, much more so with the fifth order. The IIR filter thus distorts the signal more than the FIR – especially the fifth order IIR – which is due to the nonlinear phase response of the IIR. From the previous lab, we observed that vowels are more concentrated in the low-frequency band of the spectrum, whereas consonants are in the middle- to high-frequency region. While \s\, \n\, and \r\ contribute to some middle-frequency activity, ultimately \s\ was observed to have high-frequency activity in the spectra from the previous lab. As expected, when listening to the first order filtered signals, “sip” was the artifact that had more distortion due to the IIR in comparison to the rest. Since the lowpass cutoff frequency was set at 200 [Hz], much if not all of the consonant sound \s\ was inaudible. It can be inferred that while all three consonants have center frequencies greater than 200 [Hz], “sip” had the most distortion due to high-frequency activity of \s\ in comparison to the other two consonants. In contrast, “iaia” had the least distortion due to IIR (and definitely even less distortion due to FIR). Since vowels are low-frequency phonemes, they are more centered at fundamental frequencies that are well within the established cutoff frequency.

When applying filtfilt.m to the raw data, the FIR-filtered data, and the IIR-filtered data using the filter components defined by the IIR, all twelve sound clips are muffled and not as clear as the FIR filter alone; interestingly, the raw data, the FIR data, and the IIR data sound similar to one another when the filtfilt.m is applied for each sound. However, when plotting the data sets as seen in Figure 10, we see there is no time delay between the signals, indicating that filtfilt.m is a zero-phase filter that applies no time delay to the signal of interest. In a sense, in order to create a zero time-delay signal, the blurring of transients must sacrificially be done since filtering is done both forwards and backwards in time.

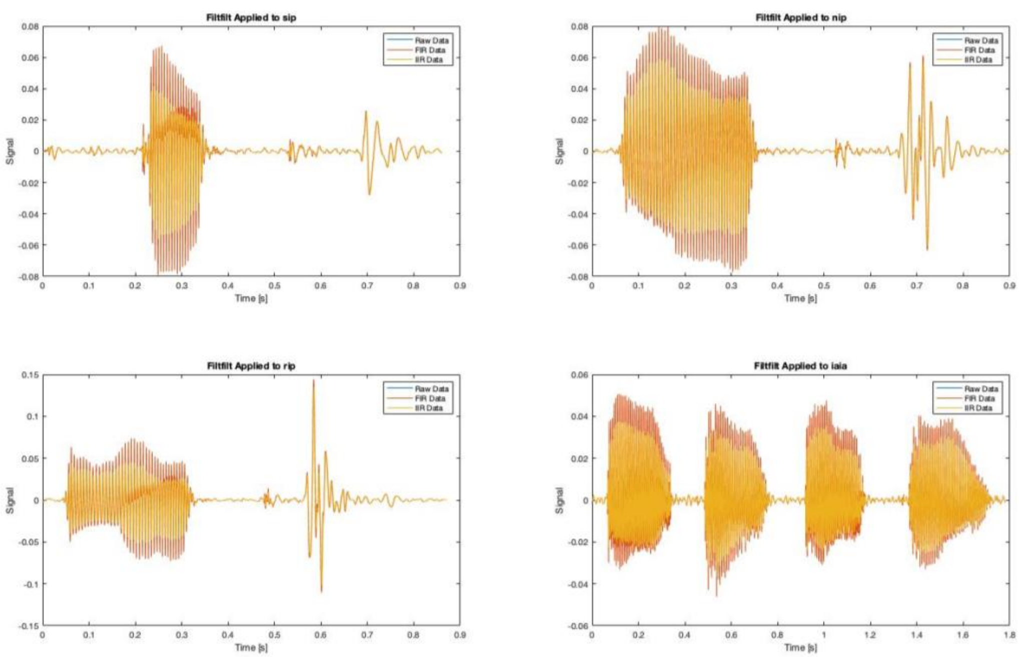

Figure 10. Application of filtfilt.m to sound artifacts. The function filtfilt.m is applied to the sounds “rip” (top left), “nip” (top right), “rip” (bottom left), and “iaia” (bottom right). The blue curves indicate raw data with filtfilt.m applied, the red curves indicate FIR data with filtfilt.m applied, and the yellow curves indicate IIR data with filtfilt.m applied.