Lab 15: ECG Circuit - Analog Filtering and A/D Conversion
Lab 16: Digital Signal Manipulation of the ECG Signal

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December 9, 2020

Introduction

For Lab 15, the objective was to process the ECG signal in the analog domain to reduce noise and prepare the signal for A/D conversion. Since large DC levels can interfere with the scaling of the ECG, the first filter added to the ECG circuit was a high-pass filter that would filter out the frequency around 0*Hz*. Next, in order to filter out any high frequency noise, a low-pass filter was added and connected to the output of the high-pass filter. Finally, to read the ECG signal, the instrumentation amplifier was connected to the input of the high-pass filter and an oscilloscope was connected to the output of the low-pass filter.

For Lab 16, the objective was to process the ECG signal in the digital domain to reduce interference and improve the quality of the ECG signal. While higher frequencies were filtered out in Lab 15, 60*Hz* interference is common and was within the passband of the filters. As a result, to improve the quality of the ECG signal digitally a notch filter was applied at 60*Hz* and at harmonics of 60*Hz*.

Results

Part 1 - Conditioning ECG Signal for the A/D Converter: Remove DC Signal Components

In order to begin conditioning the ECG signal for A/D conversion, the DC components of the signal needed to be removed. DC signals have a frequency of 0*Hz*, so in order to filter out any DC components a high-pass filter needed to be created with a cutoff frequency of 0.2-03.*Hz* (Appendix 1). Using the electrical components available, a high pass filter was created with a 1*μF* capacitor and a 470*k*Ω source resistor, achieving a cutoff frequency of

$$f_c = \frac{1}{2\pi C R_s} = \frac{1}{2\pi(1\mu)(470k)} = 0.339Hz$$

For the purpose of testing the filter, the 470*k*Ω filter resistor was used, causing the gain of the filter to be -1 (Fig. 1)

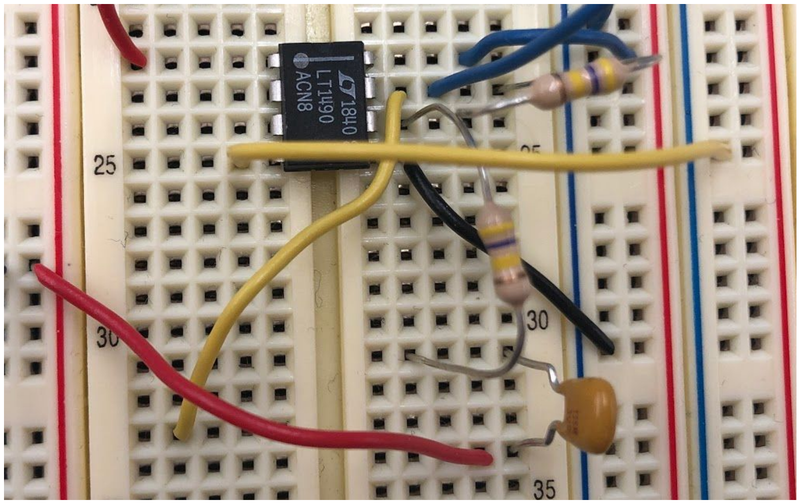


Fig. 1 - High-Pass Circuit

In order to test the filter, the signal generator function of the ADALM2000 was used as the input signal to the filter and two sets of oscilloscope leads were placed, with one set measuring the input signal and the other set measuring the filtered output signal. To ensure that the filter was functioning properly and had the correct cutoff frequency, an input signal in the stopband, passband and at the cutoff frequency was tested. First, to test a signal in the stopband, an input with *a* 100*mV pp* signal and a 100*mHz* frequency was passed through the filter (Fig. 2).

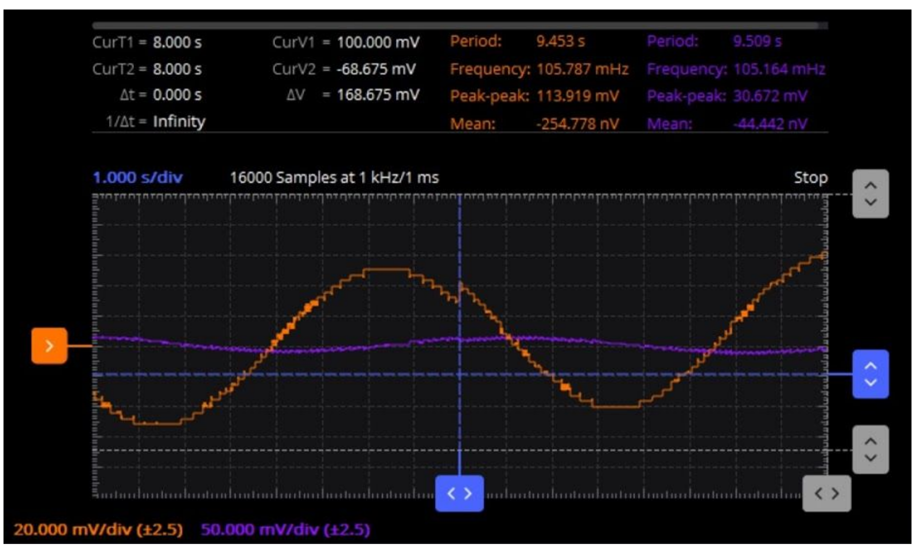


Fig. 2 - High Pass Filter Stopband Test at 100*mHz* (Input is Orange, Output is Purple)

By analyzing the oscilloscope measurements in Figure 2, it could be seen that the high pass filter was able to significantly reduce the signal within the stopband. Next, to test a signal in the passband, an input with *a* 100*mV pp* signal and a 200*Hz* frequency was passed through the filter (Fig. 3).

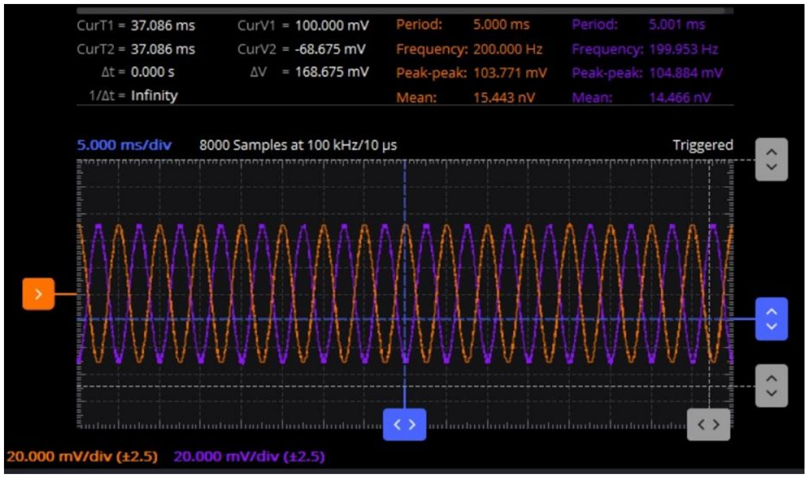


Fig. 3 - High Pass Filter Passband Test at 200*Hz* (Input is Orange, Output is Purple)

By analyzing the oscilloscope measurements in Figure 3, it could be seen that the high pass filter did not reduce the amplitude of the signal within the passband. Finally, to test a signal at the cutoff frequency, an input with *a* 100*mV pp* signal and a 339*mHz* frequency was passed through the filter (Fig. 4).

Fig. 4 - High Pass Filter Cutoff Frequency Test at 339*mHz* (Input is Orange, Output is Purple)

Since the cutoff frequency occurs when the signal is equivalent to 0.707 of the maximum signal, the high pass filter was tested by confirming that the output signal at the cutoff frequency was equal to 0.707 of the input signal. In Figure 4 it could be seen that the measured input signal was 110.411*mV pp* and the measured output signal was 71.828*mV pp*. Using the measured input value, the theoretical output signal at the cutoff frequency should be

$$output \;=\; 0.707 * input = 0.707 * 110.411 = 78.06mV\,pp$$

Since the values were close, the cutoff frequency and the high-pass filter as a whole were confirmed to be working correctly.

Part 2 - Conditioning ECG Signal for the A/D Converter: Removal of High-Frequency Noise

After creating the high-pass filter to get rid of any DC interference, a low-pass filter was created to get rid of any high frequency noise. In order to create a low-pass filter that would get rid of high frequency noise and not eliminate the ECG signal, a filter needed to be created with a cutoff frequency between 200-250*Hz* (Appendix 2). Using the electrical components available, the low-pass filter was created with a 20*nF* capacitor and 31.97*k*Ω filter resistor, constructed with a 100*k*Ω and 47*k*Ω resistor in parallel, to create a cutoff frequency of

$$f_c = \frac{1}{2\pi C R_f} = \frac{1}{2\pi(20n)(31.97k)} = 248.9Hz$$

For the purpose of testing the filter, the source resistor of the low-pass filter was changed occasionally but the filter resistor in the high-pass filter was replaced with a 1*M*Ω resistor, causing the high-pass filter to have a gain of -2 (Fig. 5).

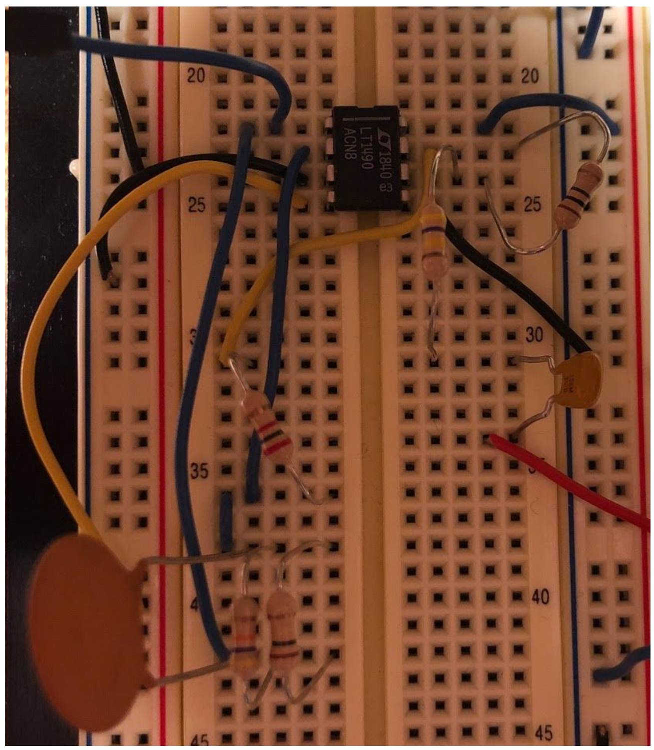


Fig. 5 - High-Pass and Low-Pass Circuit

Since the ECG signal would eventually be filtered through the high-pass filter and then the low-pass filter, the output of the high-pass filter was connected to input of the low-pass filter for testing. In order to test the filter, the signal generator function of the ADALM2000 was used as the input signal to the high-pass filter and two sets of oscilloscope leads were placed, with one set measuring the input signal and the other set measuring the filtered output signal from the low-pass filter. To ensure that the filter was functioning properly and had the correct cutoff frequency, an input signal in the stopband, passband and at the cutoff frequency were tested. First, to test a signal in the stopband, the source resistor of the low-pass filter was set to

31.97$k\Omega$, giving the circuit a total gain of -2, and an input with *a* 100mV *pp* signal and a 10kHz frequency was passed through the filter (Fig. 6).

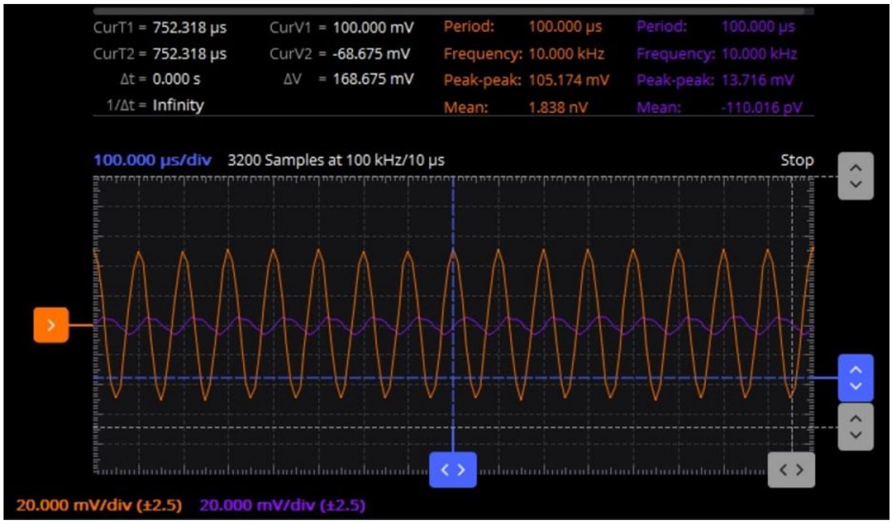


Fig. 6 - High Pass Filter Stopband Test at 10kHz (Input is Orange, Output is Purple)

By analyzing the oscilloscope measurements in Figure 6, it could be seen that the low-pass filter was able to significantly reduce the signal within the stopband. Next, to test a signal in the passband, the source resistor of the low-pass filter was set to 20$k\Omega$, giving the circuit a total gain of -3, an input with *a* 100mV *pp* signal and a 50Hz frequency was passed through the filter (Fig. 7).

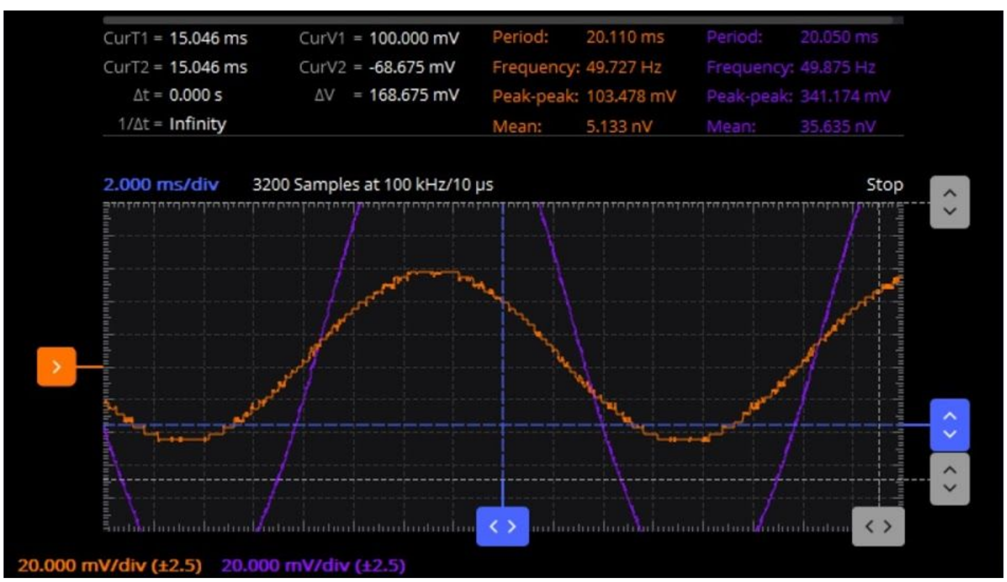


Fig. 7 - High Pass Filter Passband Test at 50Hz (Input is Orange, Output is Purple)

By analyzing the oscilloscope measurements in Figure 7, it could be seen that the low-pass filter did not filter out any of the signal within the passband and all of the signal amplification was equivalent to the total gain of the circuit. Finally, to test a signal at the cutoff frequency, an input with *a* 100*mV pp* signal and a 249*Hz* frequency was passed through the filter (Fig. 8).

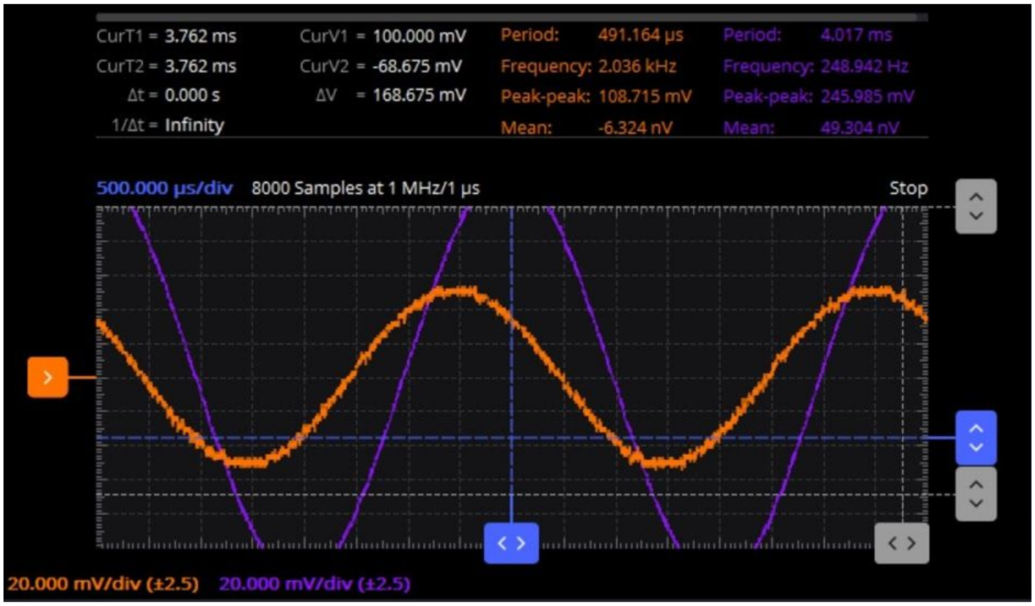


Fig. 8 - High Pass Filter Cutoff Frequency Test at 249*Hz* (Input is Orange, Output is Purple)

Since the cutoff frequency occurs when the signal is equivalent to 0.707 of the maximum signal the low-pass filter was tested by confirming that the output signal at the cutoff frequency was equal to 0.707 of the input signal times gain. In Figure 8 it could be seen that the measured input signal was 108.715*mV pp* and the measured output signal was 245.985*mV pp*. Using the measured input value, the theoretical output signal at the cutoff frequency should be

$$output \ = \ 0.707 * |gain| * input = 0.707 * 3 * 108.715 = 230.58mV\,pp$$

Since the values were close, the cutoff frequency and the filter circuit as a whole were confirmed to be working correctly.

While some components of the frequency will be removed once the signal has been converted from analog to digital, the higher frequency content needs to be removed before conversion in order to create an accurate digital reproduction. The Nyquist Theorem states that the sampling frequency needs to be at least twice the highest frequency to create an accurate reproduction, which can be done by removing the higher frequencies before conversion.

Part 3 - Acquiring an ECG Signal: Setup, Considerations and Using the ADALM2000

After ensuring that both the high and low-pass filters were functioning properly, the ECG circuit was completed by connecting the instrumentation amplifier to the input of the high-pass filter and by connecting three long wires to *+IN, -IN* and ground (Appendix 3). Additionally, in order to ensure that the signal would be large enough, the source resistor in the low-pass filter was changed to 2*k*Ω in order to create a gain of -34 (Fig. 9).

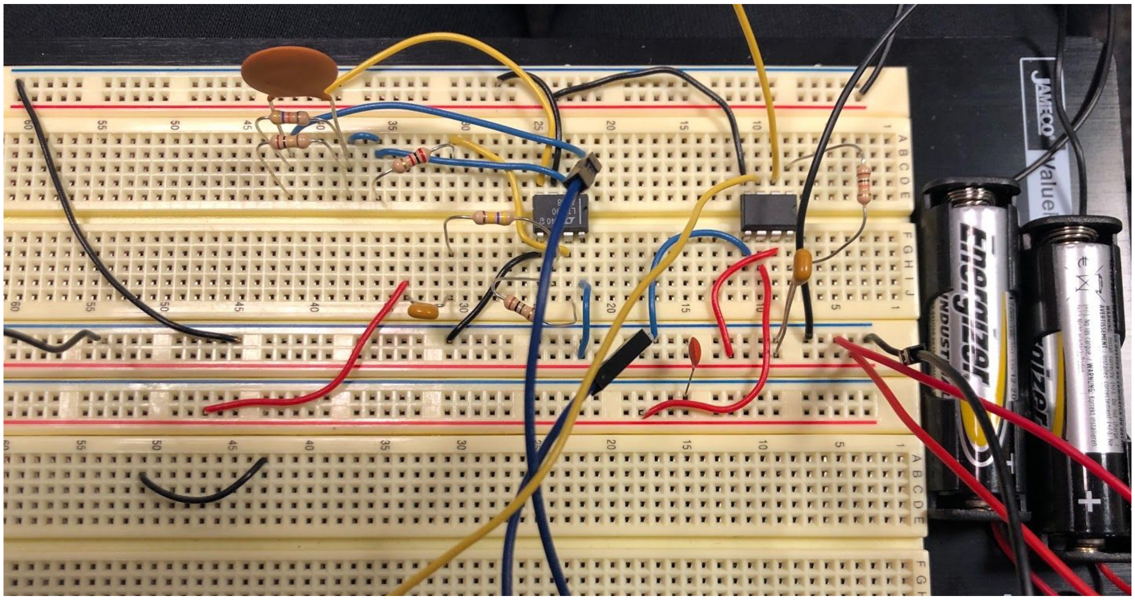


Fig. 9 - Complete ECG Circuit

Finally, three electrodes were then placed on the torso and connected to the three wires following the diagram seen in Appendix 3. Once the electrodes were placed and the circuit was complete, the oscilloscope was connected to the output of the low-pass filter and used to measure multiple ECG signals (Fig. 10 & 11).

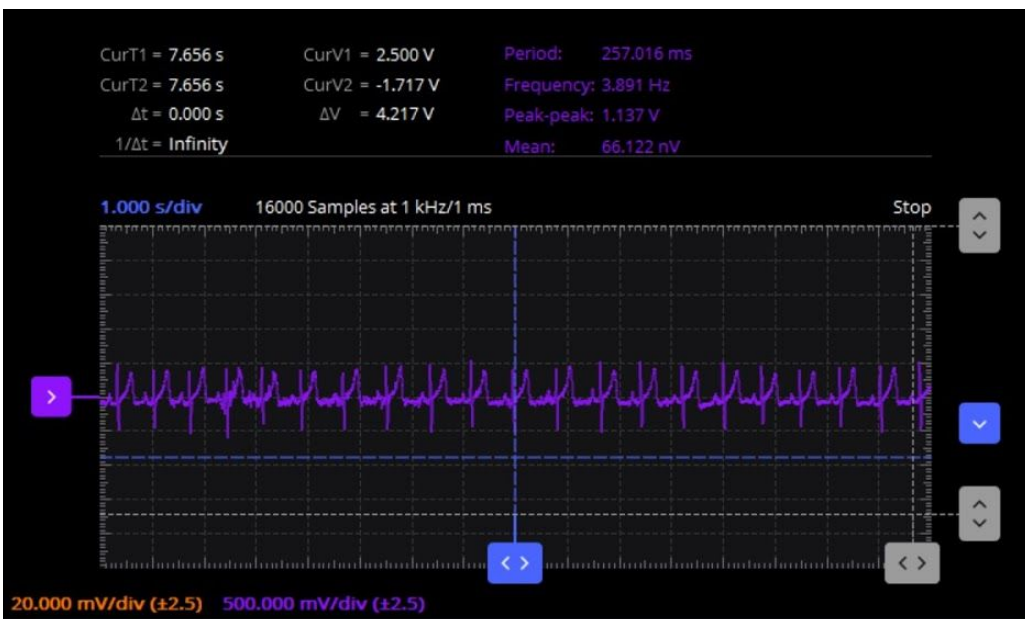


Fig. 10 - First ECG Oscilloscope Reading (1s Time Base)

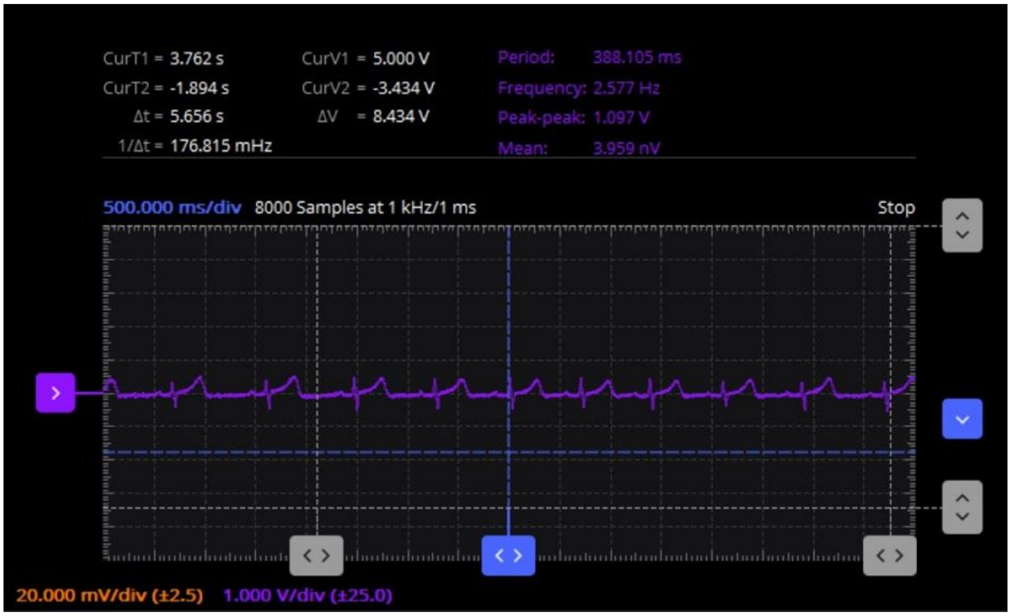


Fig. 11 - Second ECG Oscilloscope Reading (0.5s Time Base)

After ensuring that the ECG signals were reasonable, the data was exported, loaded into Matlab and plotted with and without gain (Appendix 4, Fig. 12 & 13).

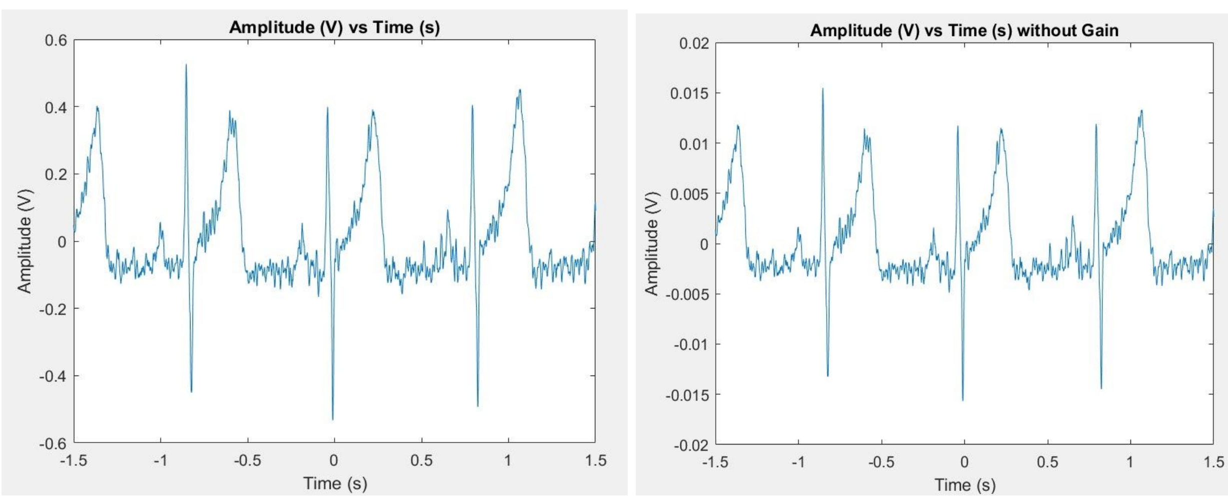


Fig. 12 - Three Second ECG1 Plot With Gain (left) and without gain (right)

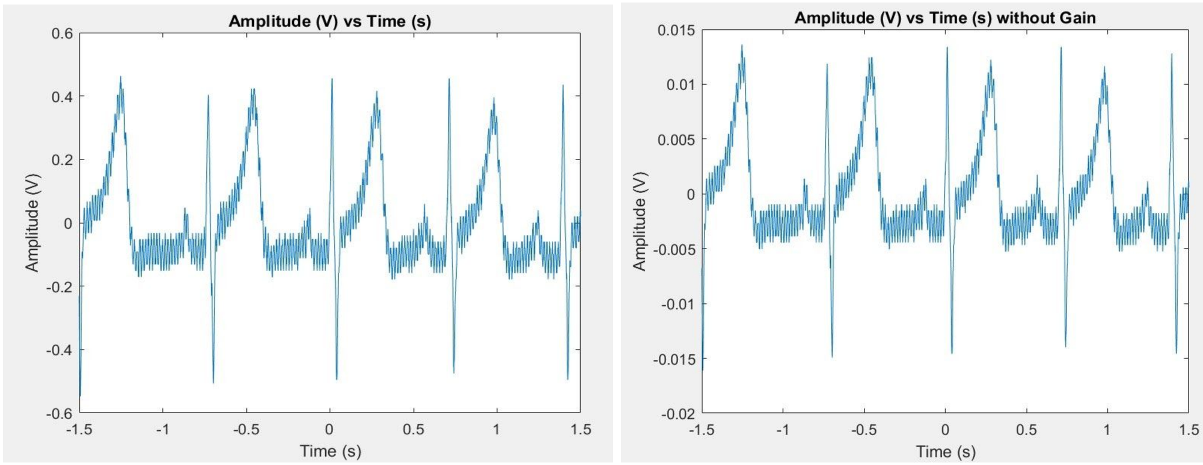


Fig. 13 - Three Second ECG2 Plot With Gain (left) and without gain (right)

Lab 16

The purpose of Lab 16 was to improve the quality of the ECG signals obtained in Lab 15 by applying a notch filter centered at 60*Hz* to remove any 60*Hz* interference. Since ECG2 was noisier than ECG1, the notch filter was applied to ECG2. First, in order to confirm that the main source of noise in the ECG was at 60*Hz*, the frequency content of ECG2 was plotted and analyzed (Fig. 14).

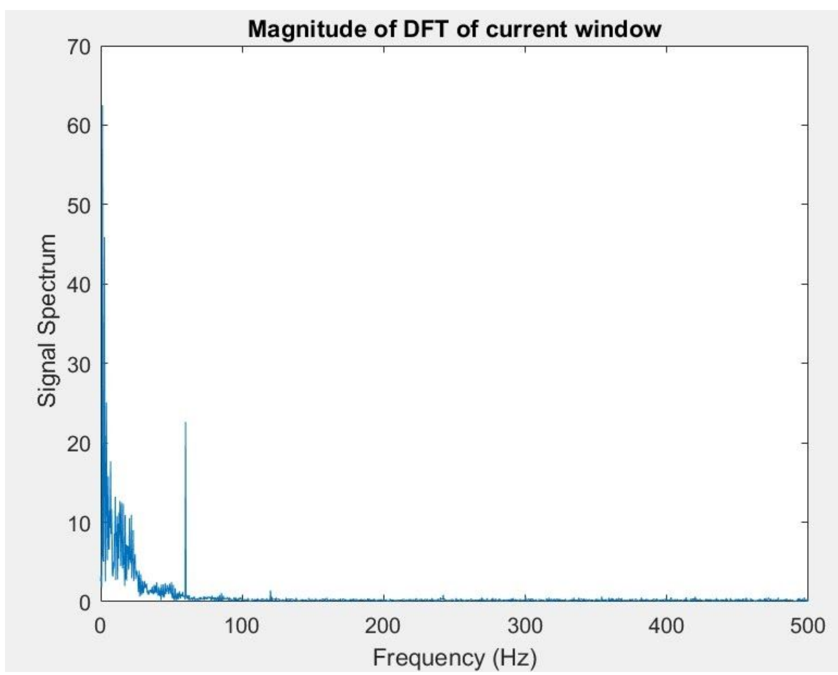


Fig. 14 - Frequency Content of ECG2

By zooming in on the isolated signal spike, it was confirmed that it occurred at 60*Hz*. In order to remove the 60*Hz* interference, a notch filter was applied to the signal by making edits to a provided Matlab code (Appendix 5). In order to confirm that the implementation of the notch filter improved the quality of the signal, the signal was plotted before and after the notch filter was added (Fig. 15).

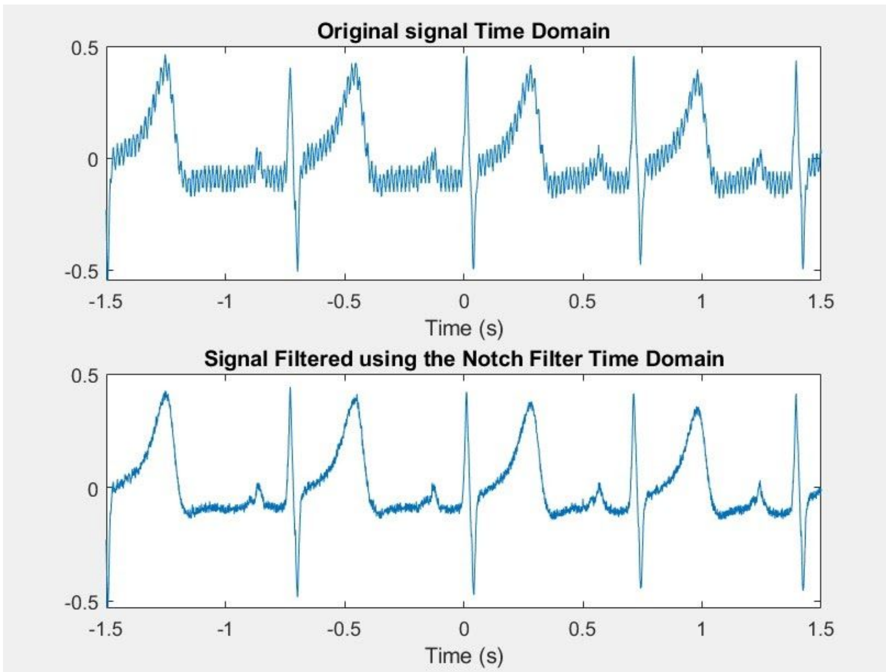


Fig. 15 - Signal without Notch Filter (top) and with Notch Filter at 60*Hz* (bottom)

After plotting the signal on the time domain, the frequency content of the filtered signal was plotted (Fig. 16).

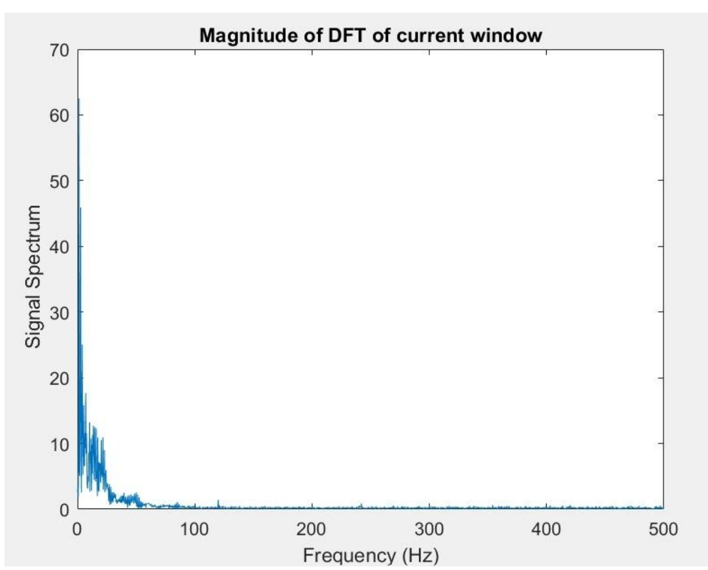


Fig. 16 - Frequency Content with Notch Filter at 60*Hz*

By comparing Figure 14 and Figure 16, it can be seen that the addition of the notch filter removed the 60*Hz* frequency spike. Since the spike at 60*Hz* was particularly prominent, it caused there to be a smaller signal spike at the harmonics of 60*Hz*. By zooming in on the small spike between 100*Hz* and 200*Hz* it became apparent that there was a small signal spike at 120*Hz*. In order to remove this signal, a second notch filter centered at 120*Hz* was applied to the already filtered signal. After filtering the signal a second time the new time domain of the filtered signal was plotted as well as its frequency content (Fig. 17 & 18).

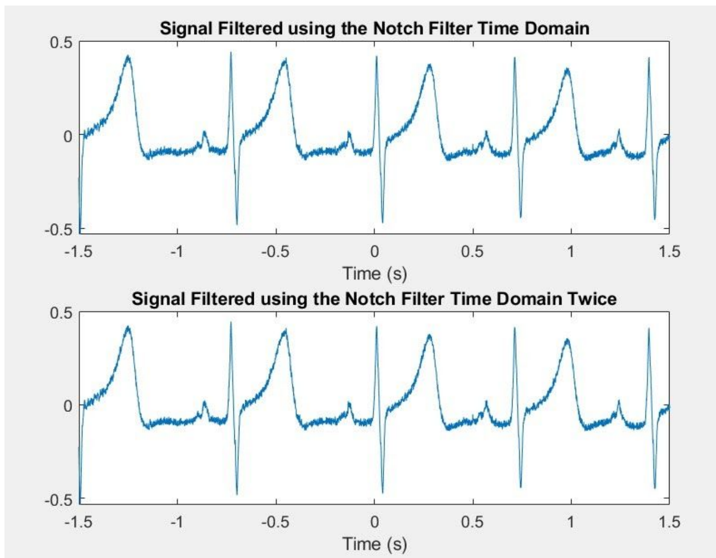


Fig. 17 - Signal with Notch Filter at 60*Hz* (top) with Notch Filters at 60 & 120*Hz* (bottom)

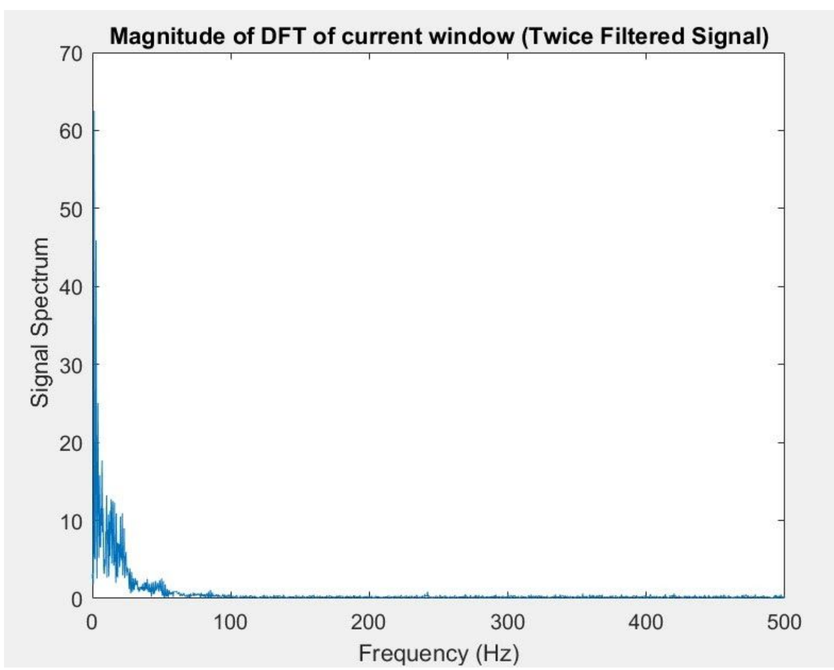


Fig. 18 - Frequency Content of Signal with Notch Filters at 60*Hz* and 120*Hz*

By analyzing the time domain plot of the filtered and twice filtered signals in Figure 15 and Figure 17 it became clear that the addition of the notch filters had effectively cleaned up the ECG signal. By analyzing the frequency content in Figure 18 it was clear that the notch filters had effectively removed any 60*Hz* and 120*Hz* interference.

Discussion and Conclusion

The objective of these labs were to process an ECG signal in both the analog and digital domain to reduce outside noise and interference.

For Lab 15, the ECG signal was processed in the analog domain by adding a high-pass and a low-pass filter. By connecting the output of the instrumentation amplifier to the input of a high-pass filter with a cutoff frequency of 339*mHz*, the DC components of the ECG signal were filtered out. By then connecting the output of the high-pass filter to the input of a low-pass filter with a cutoff frequency of 249*Hz*, any high frequency noise was filtered out as well. Each of the filters was tested by creating an input signal in the stopband, passband and at the cutoff frequency. After confirming that both of the filters were working properly, two electrodes were connected to *-IN* and *+IN* with a third electrode connected to ground. By connecting an oscilloscope to the output of the low-pass filter, an ECG signal was collected and then exported for use in Lab 16.

For Lab 16, the ECG signal obtained in Lab 15 was processed in the digital domain using Matlab. By uploading one of the ECG signals and plotting the frequency content, it was easy to see that there was a significant amount of 60*Hz* interference. However, by filtering the signal through a notch filter centered at 60*Hz*, the interference was reduced and the ECG signal became cleaner. Since the original 60*Hz* interference was so high, there was interference at the harmonics of 60*Hz* as well. In order to remove this, a second notch filter was centered at 120*Hz* and the already filtered signal was passed through. By analyzing the frequency content of the filtered signal, it could be seen that the signal at 60*Hz* and 120*Hz* was removed and the time domain showed a much cleaner final signal.

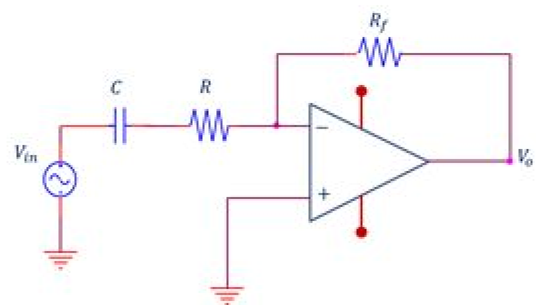
References

[1] Dr. Iman Salama, “Lab 15 ECG Circuit - Analog Filtering and A/D Conversion ”, Northeastern University, 20 July 2020

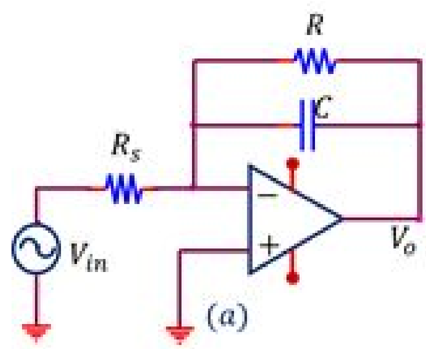
[2] Dr. Iman Salama, “Lab 16 Digital Signal Manipulation of the ECG Signal”, Northeastern University, 9 December 2020

Appendices

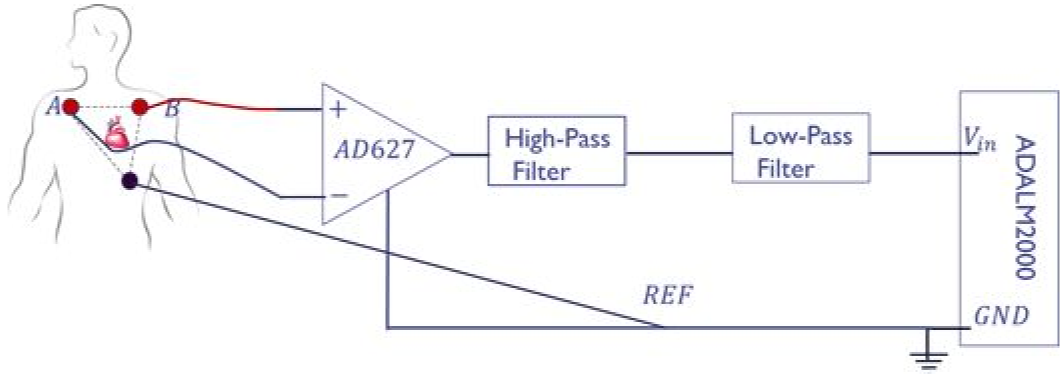
Appendix 1 - High Pass Filter Circuit Diagram



Appendix 2 - Low Pass Filter Circuit Diagram



Appendix 3 - Signal Path for ECG



Appendix 4 - Lab 15 Matlab Code

```
gain=34;
load('ECG22.csv'); %loading the data file
t=ECG22(:,2); % column 2 is the time axis
data=ECG22(:,4); %column 3 is channel 1 data
data2=(ECG22(:,4))/gain;
figure(1)
plot(t, data);
xlabel('Time (s)');
ylabel('Amplitude (V)');
title('Amplitude (V) vs Time (s)');
figure(2)
plot(t,data2);
xlabel('Time (s)');
ylabel('Amplitude (V)');
title('Amplitude (V) vs Time (s) without Gain');
```

Appendix 5 - Lab 16 Matlab Code

```
load('ECG12.csv');          %loading the data file
fs=1000; %sampling frequency = 1kHz
time=ECG12(:,2); % column 2 is the time axis
data=ECG12(:,4); %column 4 is channel 2 data
wo=60/(fs/2);               % normalized center frequency of the notch filter
wo2=120/(fs/2);
bw=wo/20;                   % Q is chosen to be 20
[b,a]=iirnotch(wo,bw); % obtaining filter coefficients
[d,c]=iirnotch(wo2,bw);
%fvtool(b,a);                % plots the filter frequency response
```

```
ECG_signal_filtered=filter(b,a,data);
ECG_signal_filtered2=filter(d,c,ECG_signal_filtered);

figure(2)
plot_frequency_content(data,fs);
title('Magnitude of DFT of current window (Twice Filtered Signal)');

figure(3)
subplot(2,1,1)
plot(time,data);
title('Original signal Time Domain')
xlabel('Time (s)');
subplot(2,1,2);
 plot(time,ECG_signal_filtered);
title('Signal Filtered using the Notch Filter Time Domain')
xlabel('Time (s)');

figure(4)
plot_frequency_content(ECG_signal_filtered,fs);
title('Magnitude of DFT of current window');

figure (5)
subplot(2,1,1)
plot(time,ECG_signal_filtered);
title('Signal Filtered using the Notch Filter Time Domain')
xlabel('Time (s)');
subplot(2,1,2);
 plot(time,ECG_signal_filtered2);
title('Signal Filtered using the Notch Filter Time Domain Twice')
xlabel('Time (s)');

figure(6)
plot_frequency_content(ECG_signal_filtered2,fs);
title('Magnitude of DFT of current window (Twice Filtered Signal)');
```