EECE 2510 – Circuits and Signals: Biomedical Applications

ECG Circuit 2 – Analog Filtering and A/D Conversion

Introduction:

Now that you have your basic instrumentation amplifier circuit running, in Lab ECG1, you will carefully process the ECG signal in the analog domain to reduce noise and prepare it for analog to digital conversion. You will then acquire a sampled (digital) version of your ECG signal in MATLAB using the National Instruments DAQ device you are familiar with.

Pre-lab Preparation:

1. Read the lab.
2. Bring your course notebook.

Overview

Working backward from the NI USB-6001 20 kSPS 14 Bit A/D, we need to start by looking at the specs for this device. The 6001 samples analog voltages from -10 to 10 volts and converts them to digital signals. It divides the input interval from -10V to 10V into 2^{14} parts: a total of 16384 levels. Our job in this lab is to provide a good EKG signal that fits within the -10 to 10V input window for the A/D device and then to use the A/D to sample the signal so that we have a digital signal we can work with in the computer. Since our power supply voltage is limited to +/- 1.5 V, we thus want to make the signal as "large" as possible but still avoid saturating the Op Amps. Unfortunately, even if we do the best job we can, using most of the ±1.5V range, we will still only use 15% of the A/D range, which is equivalent to using only a little more than 11 of the 14 bits of A/D resolution. An optimum design would have a 14 bit A/D with a 3 V input range. Questions: How many input ADC levels are available in our 3V window? How large is the spacing between adjacent levels?

A sketch of the signal path, with the necessary filters is shown below. You will need to design the filters and understand what each part of the circuit is doing!! Spec. Sheets for the chips you are using are available on the course web site. Some step by step advice is given below, but you will have to do some thinking and investigating on your own, and you will probably want to discuss your goals and approach with your instructors. Note that this document is not intended to give you step by step instructions, but to give you some idea what and why you are building and how to get started. Enjoy!!

Analog circuit goal #1: Deliver the largest signal that is certain to fit within the combined limits of the ±1.5V supply rails to take best advantage of the A/D range and have the minimum amount of noise in the converted signal. Note that you will not want to have all the gain in the instrumentation amplifier stage. This is because you will have some DC or near-DC signal

components that you must filter out before you can fully amplify the AC portion of the signal. So, expect to design an in-band gain of more than one into the filter stages to achieve the signal size that you want.

Analog circuit goal #2: Filter out frequency components that are not part of the ECG signal. A) Get rid of the DC part of the signal after the instrumentation amplifier. B) Get rid of high-frequency noise before A/D to keep the high frequency noise from appearing as part of the low-frequency signal due to sampling rate limitations.
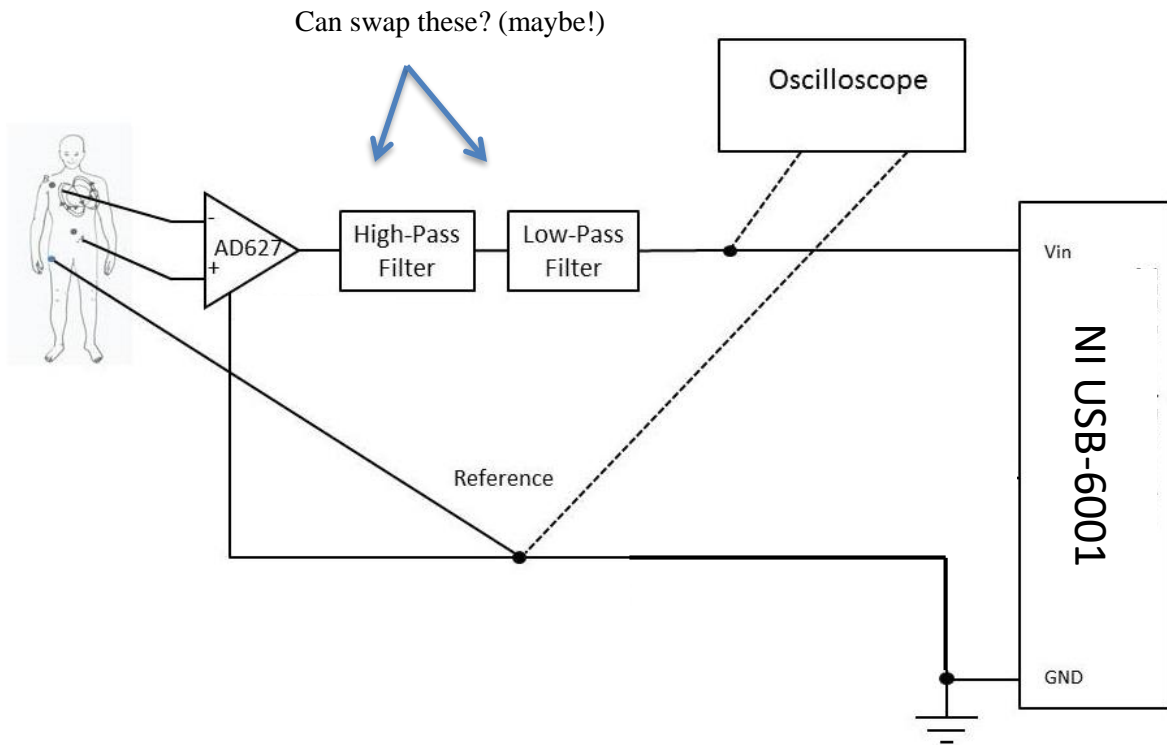

Figure 1: Signal path for ECG filtering and data acquisition

Part I, Conditioning the ECG Signal for Input Into the A-to-D Converter

Overview: Our overall goal is to provide a clean, properly shifted and scaled ECG signal to the input of the National Instruments A/D.

The raw output of the first instrumentation amplifier stage contains the desired ECG signal, but it also contains a lot of high-frequency noise, and some dc or near-dc voltages related to electrode contact potentials on the skin and perhaps other sources, and it may contain a significant amount of 60 Hz interference. We would like to remove as much of this undesired noise and interference as possible by the time we are finished, so that we have a good ECG signal to work with.

Since the DC levels (if too large) may interfere with optimal scaling of the ECG signal, you should use a high-pass filter to remove the near-DC components of the signal.

The high frequency noise must be removed before the ADC, because as you know, if the sampling frequency is not high enough, we will experience aliasing of the signal and some of the high frequency noise will appear as low-frequency noise in the digital representation of the ECG signal. To remove the high frequency noise you should use one or more low-pass filters. The signal will be greatly improved by this step! Note that filtering out too much of the high-frequency spectrum will make the signal look less noisy, but it may alter the signal by, for example, decreasing the height and sharpness of the QRS complex.

Filtering out the 60 Hz interference without affecting the rest of the signal is difficult in the analog domain, but fortunately the 60 Hz interference can at least partially be handled by digital processing on the computer. However, we should take steps (described later) to minimize the 60 Hz interference in the first place.

1. **Remove DC signal components:**

To remove the DC component of the signal coming out of the AD627 chip you should use a high-pass filter. Note that both first and second-order circuits are easy to build with one op-amp, with the second-order filter having better performance at the expense of slightly greater design complexity. We want this filter to remove the DC component (zero frequency!), but we don't want it to filter out any ECG frequencies. Discuss your ω_C (f_C), capacitor, and resistor choices with your instructor. In practical terms, it is important not to use resistors below about 1kΩ so that the op-amp does not exceed its output current capabilities. Use the 8032 op-amp, which is capable of operating at our relatively small ±1.5V power supply. Note that the 8032 chip is a dual op-amp (meaning that two op-amps are on one chip – see the pinout on the spec sheet) and has somewhat better specs than the 741. This is both good and bad. On the positive side, you should experience less offset due to op-amp input currents, and the output voltage is capable of coming much closer to the power supply. On the other hand, the 8032 is capable of amplifying higher frequency signals, so it is more prone to oscillation if the wiring is not compact and if bypass capacitors are not used. Draw the circuit for your filter in you lab notebook.

In your notebook, write down the values of R and C you used, the cut-on frequency ω_c in rad/s and f_c in Hz, and explain why you picked these values. Connect this second stage to the first stage and test your circuit with the small signal from the signal generator. Measure the cut-on frequency. Is it working as designed? If not, debug your design as necessary. If necessary, add bypass capacitors as described at the end of this section.

Do you find anything lacking or unexpected in the operation of your filter? What would happen if you chose a higher or lower cut-on frequency?

2. **Removal of high-frequency noise.**

You want to filter out the high-frequency noise without eliminating the ECG signal. Use a low-pass filter. The choice of cut-off frequency is critical!! Discuss your cut off frequency and filter circuit choices with your instructor. Note that again, you can easily use a first or second order filter.

You will have a trade-off between signal fidelity and noise reduction. Build your filter and compare higher and lower cut-off frequencies to assess the amount of noise reduction and whether the filter is altering the signal by removing too many high frequency components. In particular, make sure that you are not filtering out the rapidly varying parts of the QRS complex (the sharp peak). Document the results with oscilloscope screen shots.

To improve the trade-off, keeping all the signal components you want, but removing more noise, you can build a second (or higher) order filter (see Nilsson) for even better removal of high-frequency noise. Construct a low-pass filter as discussed in class, or one of the other low-pass filters below using half of the 8032 chip.

Now determine the upper and lower cutoff frequencies of the entire circuit using the signal generator. Are these at the design frequencies? Once you have the circuit working properly, draw the entire circuit diagram in your lab notebook. Explain why it is essential to remove high frequency noise before A/D conversion, rather than afterward

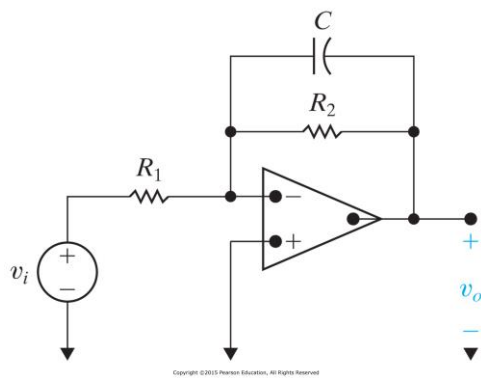**Low-Pass Filter Options:** See class notes!
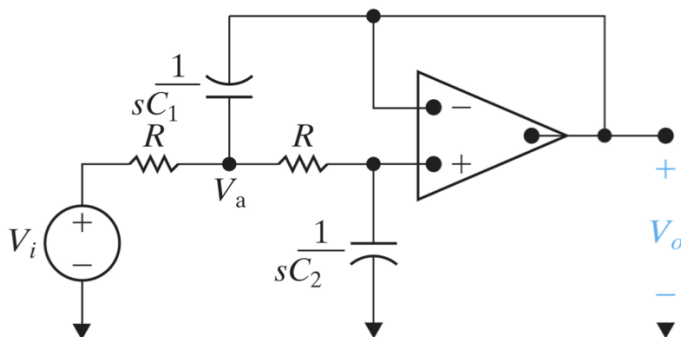

Figure 15.1   A first-order low-pass filter.

Figure 15.21   A circuit that provides the second-order transfer function for the Butterworth filter cascade.

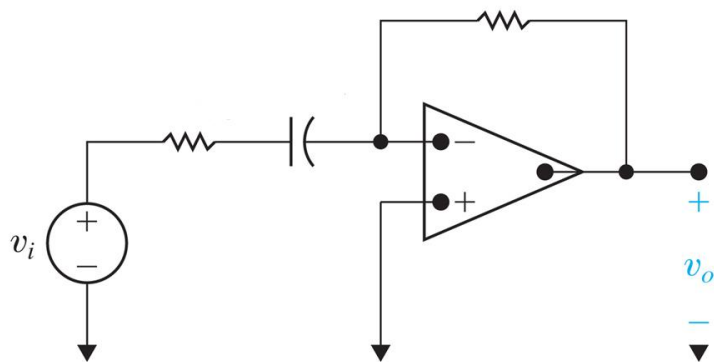**High-Pass Filter Options:** See class notes!

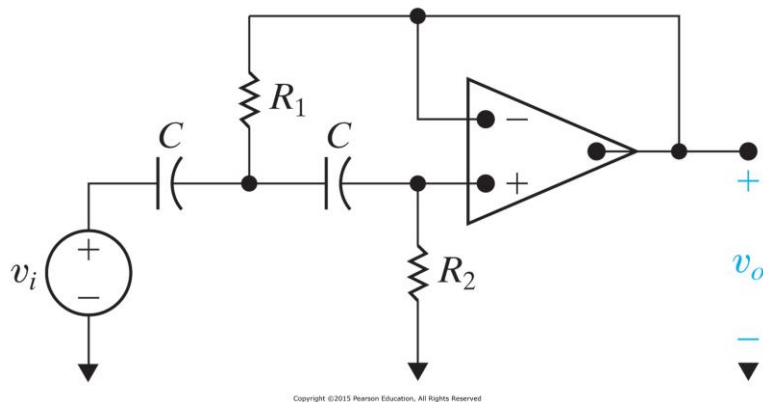Figure 15.6   A first-order high-pass filter.

Figure 15.25   A second-order Butterworth high-pass filter circuit.

Finally, see if you can reduce the noise in the circuit by adding bypass capacitors right next to the chips. You start with 3 0.1 µF capacitors, one from the + supply to the – supply, one from the + supply to ground, and one from the – supply to ground. You can try larger capacitors (in addition) to judge the effect. What is the purpose of bypass capacitors?

Part II, Acquire ECG Signal

Use the Biopac EL503 electrodes. You can use the supplied lead wires or make lead wires and attach them to the conductor by stripping a ~1" length from the end and wrapping it around the conductor tightly a few times and crimping with pliers. Do not solder since this will damage the electrode.

The Electrode placements below are suggested for the optimum signal, but simply using the right and left forearm may be more convenient for testing, and is also fine as far as acquiring a cardiac signal.

Some considerations:

1.   Electrode placement: electrodes can be placed across your chest (upper right and lower left as shown above) or on your forearms. Be sure to attach a third ground electrode to your body connected to ground. This is very important. The better contact you have between the electrodes and your skin the better chance you have of getting a good signal. Try to make sure the electrodes lie flat against your skin and that the entire electrode surface is making good contact. Try different positions of the electrodes if you are not getting a good signal – the closer to your shoulder the better, usually.

Observe the ECG signal on the oscilloscope. Remember that you want the signal to fit within the power supply rails, and be as large as possible (this is important). Describe the signal that you get. You can adjust the appropriate resistors (think about which resistors change only the gain and not the cutoff frequency!) on the instrumentation amplifier, the highpass filter or the lowpass filter to increase the gain as needed. Note that you do not want the gain of the first stage to be so large that the undesired dc component causes the amplifier to saturate.

1.   Is your circuit working as expected? Show one of the instructors your results.
     Remember: You want to "fill" the ±1.5V, but you do not want to over-fill (saturate). Modify resistors values based on the amplitude of your measured ECG signal. You can (and should) adjust this as you are working.

2.   Try to keep your muscles still when you are acquiring your data (why?). It is suggested that one student wear the electrodes and hold still, while the other student adjusts the equipment. You can even try holding your breath while acquiring to reduce movement further.
3.   This is one occasion where the "auto scale" button on the oscilloscope will probably not work.
4.   One source of noise is your body acting as an antenna and picking up low frequency signals, largely from the 60Hz power lines. We try to eliminate this as much as possible by using the difference amplifier feature of the instrumentation amplifier, assuming that the potential of your entire body is changing at the same time due to external influences. Another potential source of noise is that any loop of wire acts as a transformer as the magnetic field changes inside it. You may have seen this in your physics course and you will see it in the future if you take the electromagnetics course. One way we can eliminate loops of wire is by twisting the wires together. This is used in Ethernet cables – they contain "twisted pairs." Here, you may be able to do the same thing by twisting the three wires going to the body together. Try this and describe the results.

Part III, Acquiring an ECG Signal Using the NI A/D.

Now we are ready to acquire your ECG signal with the NI USB-6001 in Matlab. Think about what sampling frequency to use. Discuss your choice with your instructors. Once you see a good signal on the oscilloscope **acquire at least 5** 10-second long ECG traces and save them for later analysis. **Take a few longer traces** – perhaps a minute at a time to use in the signal

processing part of the lab. Try to record ECG traces with different heart rates – either from different people, or run up and down the hall a little to get the rate up!! **Note: It may help reduce 60 Hz noise if you disconnect the oscilloscope while you are acquiring the signal.** Once you have all these signals, try to move <u>very slowly</u> while recording another 10s ECG (to introduce some signal drift into the trace). The goal is to get an ECG where you see a slow change in the signal ---slower than the individual beats---without picking up too much noise. To do this you will have to change position a little without too much fast muscle contraction near where your electrodes are and without disturbing the electrode contacts. You can also try to breathe slowly while acquiring to see if you see any effect on the signal.

We will do more processing, but for this lab, plot your signal on axes scaled in units of volts and time (instead of arbitrary numbers and number of samples). Make 2 plots, one plot of the voltage as recorded by the A/D and another one scaled by the gain of your analog system so that you are plotting the actual voltage at the electrodes on your body on the vertical axis.