Experiment #9
Final Project Option 2:
Electrocardiogram
PHYS 219

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October 24, 2014

1 Objective

Using the devices you have investigated previously in this lab (OpAmps, invertors) as well as some new ones (Instrumentation Amplifier, etc.) you will build an amplifier capable of detecting and amplifying the low level, ≈ 5 mV, electrical waveform (as measured by electrodes) that triggers your heart and displaying it on an oscilloscope.

2 Introduction

As most of you are aware, the heart is triggered by impulses which are in turn produced by pacemaker cells located (in the human heart) in the right atrium. By carefully analyzing the waveform not only can the pulse rate be measured (which is simply the frequency) but numerous other medically important quantities (heart shape irregularity, etc.). The waveform can be conveniently measured with electrodes placed on a person's skin and across their heart. One challenge in observing the waveform in this fashion is its low (100 μV to 5 mV) amplitude coupled with the fact that it rides on top of a large, potentially time-varying (and uninteresting) "common-mode" voltage. In this type of application the non-ideal properties of OpAmps become important when designing the proper amplifier. For this experiment you will construct an instrumentation amplifier capable of amplifying your heart's waveform in the presence of the common-mode signal.

The existence of a small differential AC signal of interest on top of a large (and uninteresting) common-mode signal is common in many applications, not just an ECG. Figure 1 helps define the situation. If a standard inverting amplifier that you investigated in Experiment 4 is used both the differential and common-mode portions of the signal (and taking for example V_- to be ground)

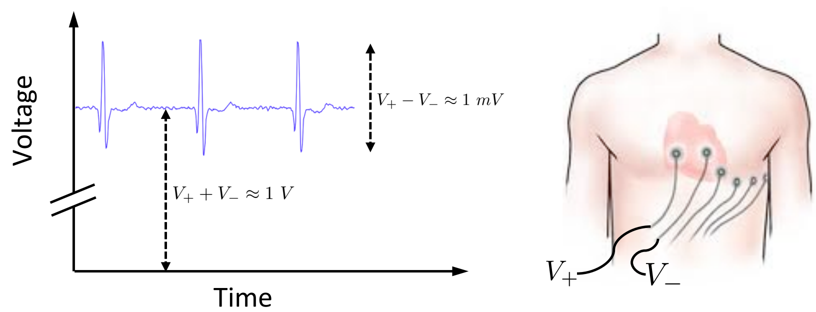

Figure 1: Diagram showing common mode ($V_+ + V_-$) and differential ($V_+ - V_-$) signals.

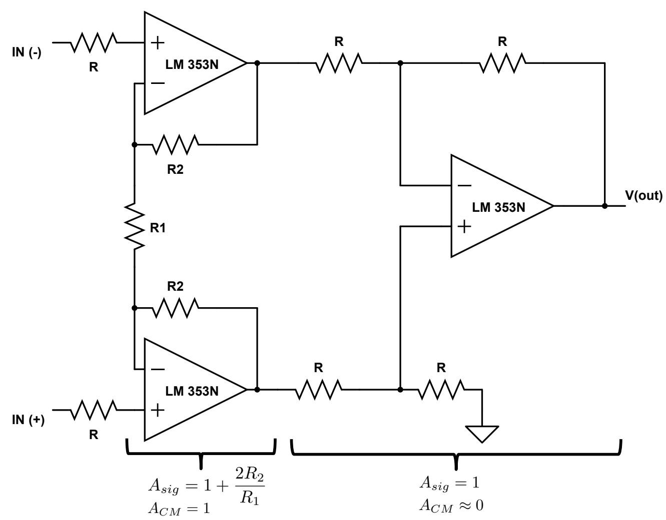

Figure 2: Instrumentation amplifier that is used amplify a differential signal with large common mode rejection.

to be amplified which leads to difficulties in obtaining large amplifications for the AC portion. What is required is a difference amplifier with a large common mode rejection ratio (CMRR). Common mode refers to the common signal that is present on both (or common to) the + and − electrodes and with reference to Fig. 1, $V_{CM} = V_+ + V_-$. An obvious second iteration in the design of an amplifier is to apply the + and − electrodes to the + and − inputs, respectively of an OpAmp configured with negative feedback. However, this will not work very well. You should discuss why this is the case in your lab report. *Hint: consider some non ideal OpAmp properties.* A very good alternative with large CMRR is an instrumentation amplifier as show in Figure 2. You should convince yourself that the amplification for the signal and common mode are as indicated and describe the circuit analysis in your report. *Hint: it is easiest to complete the analysis using superposition.* We will build a version of this type of amplifier for our ECG application.

3 Diodes

One basic component that we will use in the ECG circuit is a diode which is a device that, ideally, only allows current to flow in one direction.

4 Test Oscillator for Heart Rate

To test and troubleshoot your ECG circuit it is helpful to have a oscillator that generates a waveform with a similar frequency and amplitude as will be measured by the ECG electrodes. The first step in building this oscillator is to fully understand the MC54/74HC14A Inverters. They are a special type of inverter (known as a Schmitt-trigger Inverter) which incorporates hysteresis in the input triggering characteristic. In other words, the input voltage level required to cause the output to make a transition from one state to the other depends on which output state the inverter is currently in and is displayed in Fig. 3.

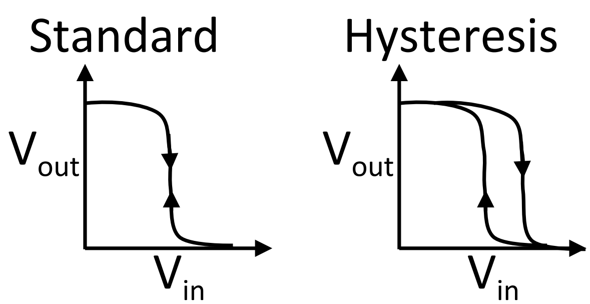

Figure 3:

Using the output of the DC. power supply as the input to one of your inverters, measure the two threshold levels of the unit. That is, determine the amount of hysteresis characterizing the device. The presence of hysteresis of this kind increases the versatility of the unit. In particular, Schmitt-trigger circuits provide excellent noise immunity and the ability to square up signals with long rise and fall times. Explain how this is possible. An application of interest to us is the ability to construct a simple square wave oscillator from such an inverter.

Next assemble the circuit shown in Fig. 4a and explain its operation. The Schmitt-trigger's should be powered with V_{DD} as V_{CC} and $V_{DD}/2$ as GND. This will put a non-zero bias on your test oscillator which is similar to the ECG condition. It will be helpful to measure the input voltage and output voltage simultaneously on the oscilloscope when describing how it works. You should build this circuit in one corner of your protoboard.

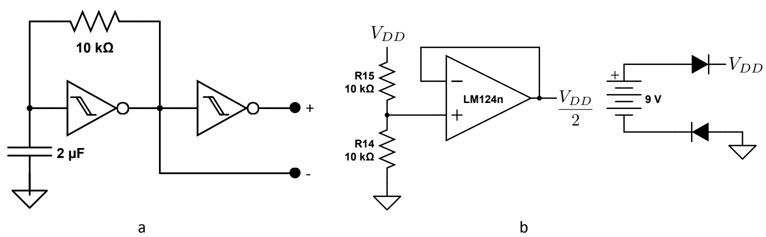

Figure 4: a) Square oscillator to provide a "test" heart-rate. b) Voltage follower to divide supply voltage by a factor of two.

After verifying that circuit produces a square wave with $\approx$ 5 Volt peak to peak amplitude, design a simple voltage divider on each inverter output (+ and $-$) to produce $\approx$ 5 mV peak to peak signal on each. Use these lower level signals as test inputs [$TEST(+)$ and $TEST(-)$] for the next section. Note that one of the larger signals ($\approx$ 5 V_{PP}) in the voltage divider is very useful as a trigger for your oscilloscope.

With the initial setup of the oscillator you probably used on the on-board 15 Volt supplies. In this experiment, we would like everything to be battery powered with a 9 Volt battery. We can easily generate a supply voltage for the inverters by dividing the (9 Volt) supply voltage by 2 and buffered with a voltage follower. Construct the circuit shown in Fig. 4b using the one of the OpAmps in the LM124n quad package and use it to power your test oscillator.

5 Amplifier

5.1 Inverting Amplifier

First construct a simple inverting amplifier (similar to Experiment 4) and attempt to differentially amplify your test oscillator by a factor of twenty (i.e., $20 \times [TEST(+) - TEST(-)]$. This will not work. Describe the result and discuss why it failed. Next, disassemble this amplifier as you won't be using it.

5.2 Instrumentation Amplifier

To address some of the shortcomings of the inverting amplifier, we will use an instrumentation amplifier shown in Fig. 5. Build this circuit using the LM124n quad package. To get the best performance it is important keep the wire lengths short. Also keep the leads on the components (resistors, etc.) short as well with the components flush to the proto-board. Power the circuit with a 9 volt battery: build the power supply circuit shown at the right of Fig 4, connecting the ground side to one of the supply rails of your board and VDD to another rail, then all chips are powered from those rails. What is the purpose of the diodes?

Use your test oscillator to confirm the operation of your instrumentation amplifier. If it doesn't work, then troubleshoot the circuit by first grounding one of the inputs and tracing through the voltages to confirm each OpAmp's operation and then repeat by grounding the second input (if necessary). Once you are absolutely sure your instrumentation amplifier is working, move on to the next section.

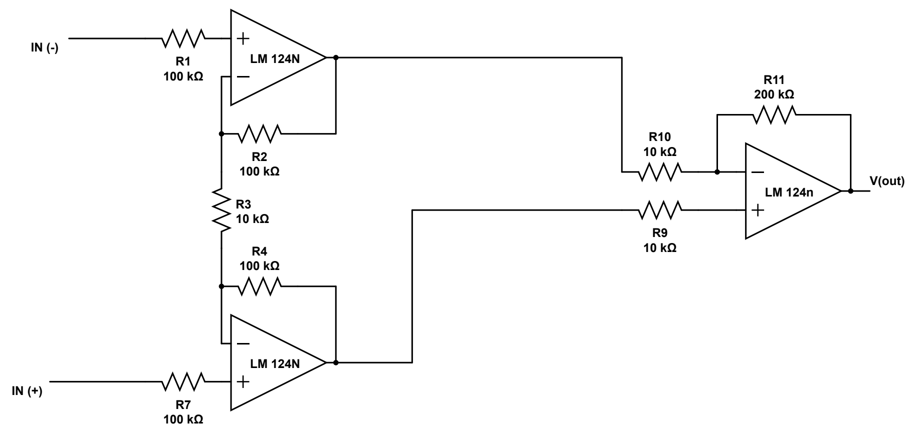

Figure 5: Preliminary version of Instrumentation Amplifier for ECG measurement

5.3 Modified Instrumentation Amplifier for ECG

Next we need to make some refinements for this instrumentation amplifier to work well in an ECG application and these modifications are shown in Fig. 6. The first upgrade addresses the condition that your body has a floating potential with respect to earth ground (which you particularly notice when you get shocked after walking on a carpet and touching a grounding source). In general this potential varies slowly over time. Discuss why this would be a problem in your lab notebook. To address this issue, we are going to hold the subject's body to a "virtual ground" of $V_{DD}/2$ using the voltage source you have already constructed previously. This requires the use of a third electrode or a "body ground" as discussed below. Note that $V_{DD}/2$ has also been connected to the + terminal of the final OpAmp in the instrumentation amplifier. You should discuss in your lab notebook why this is necessary. Finally, you need to install three pairs of diodes as shown between the three electrodes and of course discuss the reason for their inclusion in your lab notebook as well.

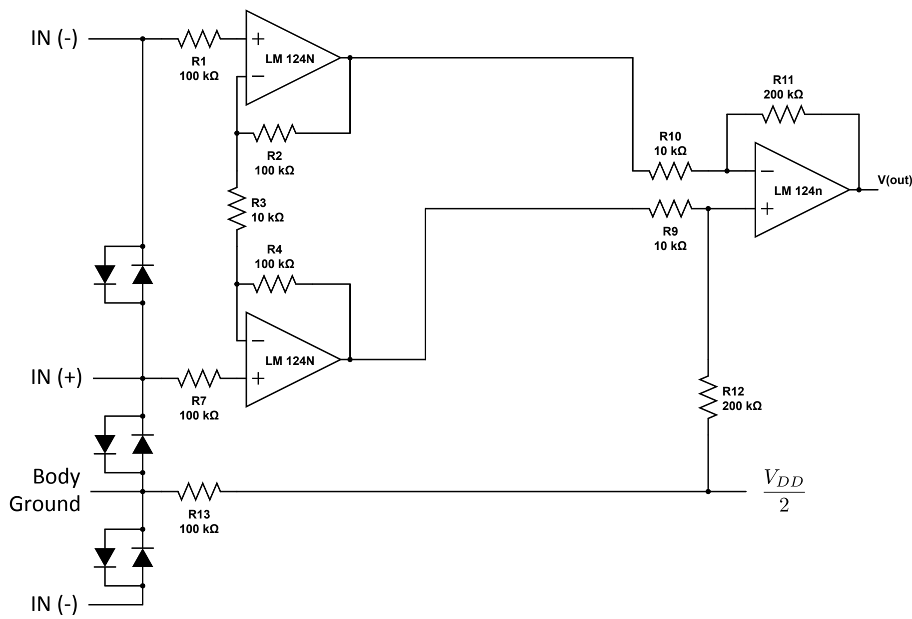

Figure 6: Final version of Instrumentation Amplifier for ECG measurement

6 ECG measurement

Now you are ready to hook up your amplifier to electrodes and (hopefully) observe your (or your partner's) heart waveform. First, go to the TA/Prof and ask for four disposable electrodes. You will only be provided electrodes if your circuit is completely isolated from any power supplies that are powered by 110AC V, (i.e. you are only using a 9V battery). You should try and reuse your electrodes for a few sessions (put them back in their packaging at the end the day), use tape to secure used ones if they aren't sticking well and supplement the electro-conductive gel if necessary.

First place the electrodes in one of the two configurations as shown in Fig. 7. The placement of the electrodes can be tricky sometimes, so to check that you have good contact at a good locations go to the front and ask the Prof/TA for help. He/She will help you hook up your electrodes to a pre-built circuit that will be able to display your ECG, thus confirming whether your electrodes are attached and located properly (you should do this each day that you re-attach the electrodes).

Next, return to your work bench and hook up your electrodes to your circuit. You should easily see your heart rate and ideally you should be able to identify the various points (usually labelled P,R,Q,S, and T) of heart's waveform. Most likely, you might have a lot of high frequency noise on your output. You should filter this noise using a low-pass filter (similar to Experiment # 2, but using a series RC circuit) at the output of your circuit. The heart's waveform has information up to $\approx 160Hz$, so the 3 dB (or break) point of your low pass filter should be around this value. Take a picture of your output before and after implementing the low pass filter to show the improvement.

After installing the low-pass filter, if you still don't see your ECG waveform, then obtain a heart pulse detector from the TA/Prof and use it to trigger your scope. Using this trigger should enable you to find a lower amplitude ECG signal. You should discuss why this would help in your lab notebook. Once you have a good picture of your ECG waveform on the scope, take a picture and identify the various points (P,R,Q,S, and T).

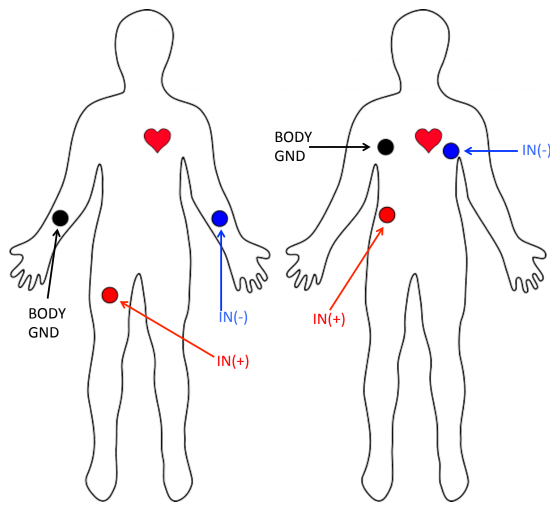

Figure 7: Placement of electrodes for ECG measurement