ECE 3110   LABORATORY EXPERIMENT NO. 5

ELECTROMYOGRAM (EMG) DETECTOR WITH AUDIOVISUAL OUTPUT

Pre-Lab Assignment: Read and review Sections 2.4, 2.8.2, 9.9.3, 13.4, 13.5, and 13.9 in Sedra and Smith. Bring your book to lab.

Objective: The goal of this lab is to build an EMG sensor with a bar-graph LED output and an audio output that both indicate the strength of a muscle contraction. The lab is outlined such that you will design and test each circuit that will be used to build a complete system. You are welcome to explore alternative methods of implementation to achieve the same goal. EMG stands for electromyogram, which is the measurement of electrical potentials created by the contraction of muscles. Internally, muscles generate voltages around 100 mV when they contract. These voltages are greatly attenuated by internal tissue and the skin, and they are weak but measurable at the surface of the skin. Typical surface EMG signals for large muscles, such as the bicep, are around 1-2 mV in amplitude. EMG signals contain frequencies ranging from 10 Hz or lower up to 1 kHz or higher. A special case of the EMG is the ECG (electrocardiogram), often referred to as the EKG (elektrokardiogram) due to its German origins, which is an EMG measurement of the heart. ECG signals are quite strong – often 3-4 mV in amplitude.

A typical EMG waveform measured over the bicep is shown below during a brief muscle contraction:
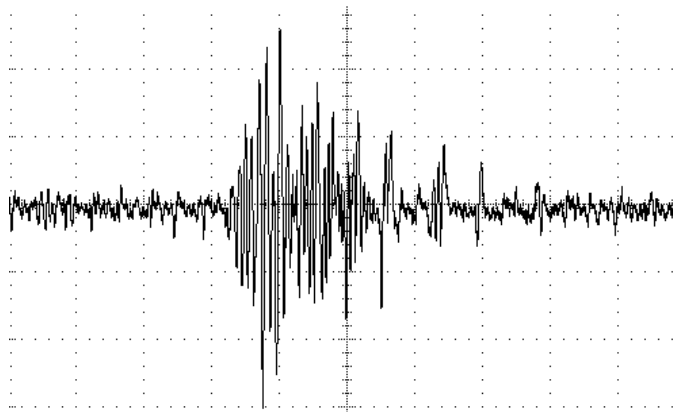
Here, the time scale is 200 ms/division.

In this lab, we will develop a sensitive circuit to amplify and filter the EMG signal, then process the signal (in analog electronics) to compute the strength of the signal, and display this on a four-level bar-graph LED display. We will then build a circuit that

translates voltage into frequency and drives a speaker to give an audio cue based on muscle contraction.

## Part I: Instrumentation Amplifier Front-End

A. Background

Before proceeding with this section, you should first read Section 2.4 ("Difference Amplifiers") in Sedra and Smith, 5th edition.

To observe an EMG signal, we need to build a differential amplifier with high common-mode rejection, since the dominant voltage signals on our bodies is usually a 60-Hz sine wave that is capacitively and/or inductively coupled to us from the 120-VAC wiring in the walls. We can reject this "global" signal by looking at the difference in voltage between two nearby points on the skin over the muscle of interest (and rejecting common signal common to both electrodes). We will also want to use a circuit the draws nearly zero current from the input leads, since dc current passed through EMG electrodes can lead to large dc offsets and degrade the long-term usefulness of the electrodes.

The circuit that satisfies these criteria is an instrumentation amplifier (see Fig. 2.20 in Sedra and Smith) built from JFET-input op-amps. Most common op-amps, such as the LM741 and LM324, have bipolar transistors (BJTs) as input devices. This leads to input currents of 100-500 nA. This may seem like a small amount of current, but we can do better. Certain op-amps use junction FETs (JFETs) in their input differential pair, and these op-amps have input currents of 0.2 nA or less! (Op-amps using MOSFETs for input devices have even lower input currents, but they generally exhibit higher levels of noise and are easily damaged by static electricity.)

In this lab, we will use the TL084, a quad JFET-input op-amp in a 14-pin DIP package. The pinout of the TL084 is identical to that of the LM324 and many other quad op-amps, and is shown below:
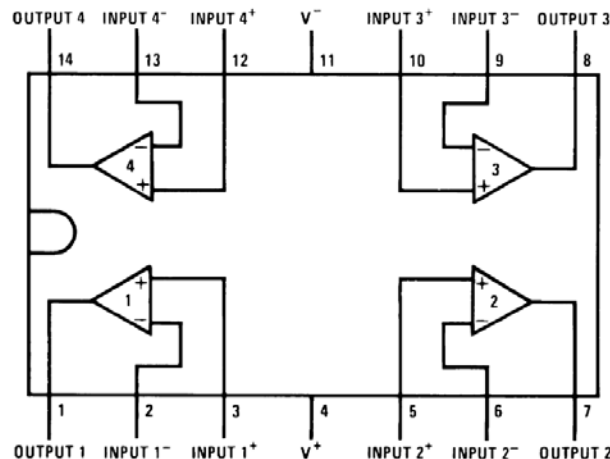
V+ and V- are the positive and negative power supplies. In this lab, we will power everything with +9V and -9V, supplied either from a benchtop DC power supply (for

tests not involving connection to the body) or two 9V batteries (for any tests where you connect the circuit to your body via EMG electrodes). **For safety reasons, you should never connect the circuit to your body (via EMG electrodes) unless it is powered only from batteries and completely disconnected from any power supplies that are plugged into the wall.**

B. Design, Build, and Test

Now, build an instrumentation amplifier as shown in Fig. 2.20(c). Design the circuit for an overall gain of 201, and use 10 kΩ resistors for "$2R_1$", R_3, and R_4. What value do you need to use for R_2? To test the circuit, tie v_{I2} to ground and connect v_{I1} to a function generator. Apply a small-amplitude 1-kHz sine wave to the circuit. If you observe clipping on the output then you may need to build a resistor voltage divider to further attenuate the function generator signal. What is the measured gain of your circuit? Is it what you expect? (Remember to set your function generator to "HI-Z" output mode, or your measurements will be off by a factor of two!)

Now, measure the 3-dB bandwidth of this circuit. Increase the input frequency until the gain drops by a factor of $\sqrt{2}$. (This is the high 3-dB cutoff point.) Download the TL084 datasheet from the Texas Instruments website (www.ti.com) and find the "unity-gain bandwidth" of the op-amp. This is the 3-dB bandwidth of the op-amp *if it is configured to have a gain of one*. Remember, the gain-bandwidth product of op-amp circuits is *constant*. Based on this, what is the theoretical prediction of your circuit's bandwidth? How does it compare to your measured value?

- Demonstrate the operation of your instrumentation amplifier to your T.A. (10 points).

Now let's observe some actual EMG signals using this circuit. First, make sure the circuit is powered by batteries. Next, get a package of BioTec EMG electrodes. This package contains three adhesive electrodes with attachment points for clip-on wires (or alligator clips). Stick two of these electrodes over your bicep, close to each other but not overlapping. Stick the other electrode on the bony part of your elbow (of the same arm). Connect your elbow to circuit ground. This will keep your body potential near your circuit's ground potential. Since there are no muscles at your elbow to generate electric potentials, this is a good grounding point. Connect the other two electrodes to v_{I1} and v_{I2}. Observe the output of your circuit on an oscilloscope and try flexing your bicep. For best viewing, set the horizontal scale to 500 ms/division, and put the scope on "roll" mode.

You should observe amplitudes of 100-300 mV during muscle contraction. If you see a lot of 60-Hz noise, try rearranging the wires coming from the electrodes, or bunching them close together. You may also observe a large DC offset on your signal. An offset of a few millivolts at the electrode-skin interface, and unfortunately this offset is amplified along with the EMG signal. You can switch your scope to "ac input" to get rid of this for now, but we need a circuit solution to the problem.

We will add a simple RC highpass filter to eliminate the dc offset voltage. Add the following circuit to the output of your instrumentation amplifier:
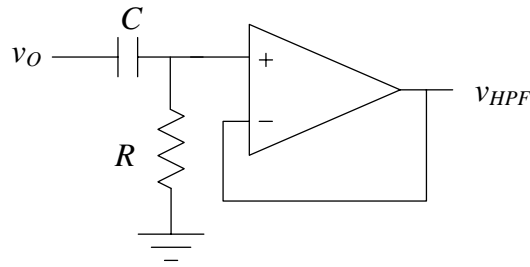

(Use the one remaining op-amp in your TL084 chip to implement the unity-gain buffer.) Derive the cutoff frequency of this circuit. Pick component values to give a cutoff frequency of roughly 10 Hz (plus or minus 30%). A 1-µF monolithic capacitor is recommended for C. Now put your scope back on dc-coupled input, and observe v_{HPF} while you contract your bicep. Is the dc offset gone?

- Demonstrate the design of the high-pass filter and operation of this circuit to your T.A. (10 points).

Part II: Envelope Detector

We would now like to add a circuit that will give us a "running average" of the amplitude of the EMG signal. The first step in calculating the amplitude of this signal is to rectify it, so we only see the positive swings of the signal. You should be familiar with the use of diodes to rectify signals. However, diodes need approximately 700 mV of forward bias before they begin conducting, and our signals (after amplification) are less than this. Instead, we must use a "precision rectifier" circuit, as shown in Fig. 13.34 in Sedra and Smith. Build this circuit using 1N4148 diodes. Use an LM324 quad op-amp (same pinout as the TL084) powered from +9V and -9V for the amplifier. Connect the input of this circuit to the output of your high-pass filter.

Test the circuit with sine waves, and with EMG signals. Observe both the output of the high-pass filter and the output of the precision rectifier simultaneously on your scope. For EMG signals, you should see something like this:
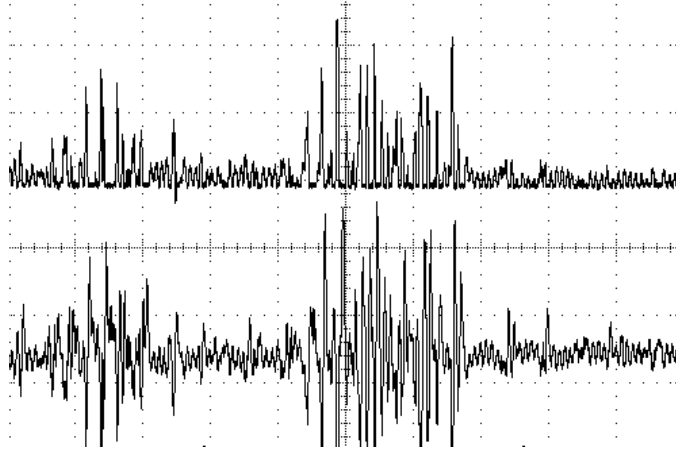
- Demonstrate the operation of this circuit to your T.A. (10 points).

Next, we need to smooth the rectified signal to generate an "envelope" of the signal, as shown below:
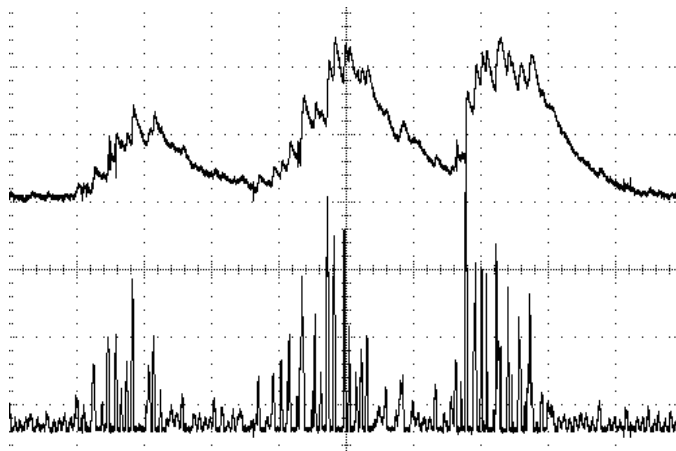
We will add a low-pass filter to the rectifier, as shown in Fig. 13.35 in Sedra and Smith. (Note that the first op-amp in this schematic forms the precision rectifier.) Note that this circuit can amplify as well as filter: The gain is set by $-R_4/R_3$ (the circuit is inherently inverting), and the cutoff frequency is set by $f_c = 1/(2\pi R_4 C)$. Use $R_3 = 10$ kΩ, and select component values that give you a gain between -10 and -20, and a cutoff frequency in the range of 0.5 Hz – 2 Hz. You may wish to try different cutoff frequencies and observe the effect of this parameter while applying EMG signals to the circuit. There is a trade-off between response time and the smoothness of the envelope signal.

Now apply an EMG signal and observe the output of the precision rectifier and the output of your low-pass filter simultaneously on the scope. Using the scope, invert the channel that is connected to the low-pass filter to compensate for its negative gain.

- Demonstrate the operation of this circuit to your T.A. (20 points).

- Write down typical voltage levels from your envelope signal for no muscle contraction, weak muscle contraction, and strong muscle contraction. These rough measurement will be useful in Parts III and IV.

Part III: LED Bar-Graph Display

Finally, we will create a four-LED bar-graph display to act as a "muscle strength" indicator. The four LEDs will act as a "thermometer" display – with no EMG activity, all LEDs will be dark. Then as the EMG activity increased in amplitude, more and more LEDs will light up. To accomplish this, we will essentially build the front-end of a 2-bit flash analog-to-digital converter (see Section 9.9.3).

Essentially, we want to create four thresholds, shown conceptually as horizontal lines in the example below:
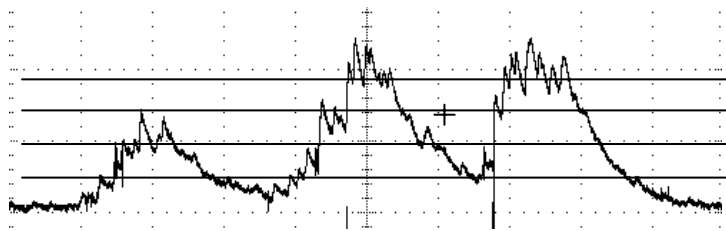
We will trigger a different LED when the envelope crosses each threshold point.

For comparing two voltages and producing a digital ("greater than" or "less than") output, we will use an LM339 quad comparator chip. The pinout of this chip is shown below:
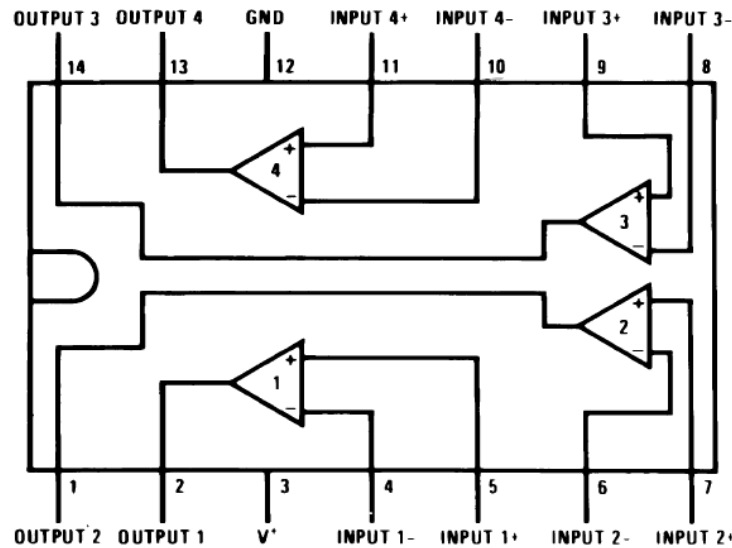
(If you are wondering why the pinout of this quad comparator is different than that of the quad op-amps, it is because in a comparator, you don't want feedback from the digital

output signals to the sensitive analog inputs – it can lead to oscillations in many circuits. Thus, the outputs are kept as far from the inputs as possible.) Connect the V+ pin to +9V and the GND pin to -9V. (If this seems strange, keep in mind that a chip doesn't know the difference of being powered from +9V/-9V or being powered by +18V/0V; either way, it's 18V of total power supply voltage.) You may also with to tie a 0.1 μF capacitor across the power supply pins of the chip to help reduce power supply noise with the comparators switch state.

The outputs of these comparators are "open collector." This means that the output pins are tied to the collector of an npn transistor in the chip. This transistor is either turned off when V+ > V- or it is turned on (i.e., in saturation) when V+ < V-. To read the output as a voltage, we would need to add a pull-up resistor to the positive power supply. However, there is a very straightforward way to use this comparator to drive an LED:
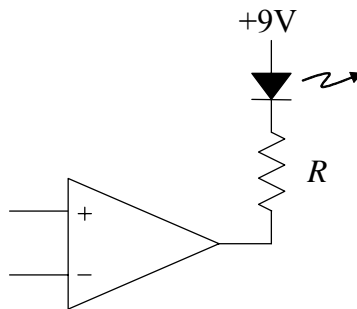
When V+ < V-, the output of the comparator should be pulled down close to -9V by the internal npn transistor. Find a value of R that limits the LED current to 5-10 mA. Remember that the forward voltage drop across LEDs is usually around 2 V (much higher than 0.7 V for normal diodes). Connect a resistor and LED to one comparator, and connect its inputs to various voltages to verify that the comparator and LED work properly.

Now, we will use a resistor ladder to create the appropriate thresholds for comparison. Keep in mind that the output of our rectifier/low-pass filter is a negative voltage, so we will need to generate negative voltages for comparison. The basic idea of the circuit is diagrammed below:

0V (ground)

R_1

V_1

+9V

R

R_1

+9V

V_2

R

R_1

+9V

V_3

R

R_1

+9V

V_4

R

R_2

EMG
envelope

-9V
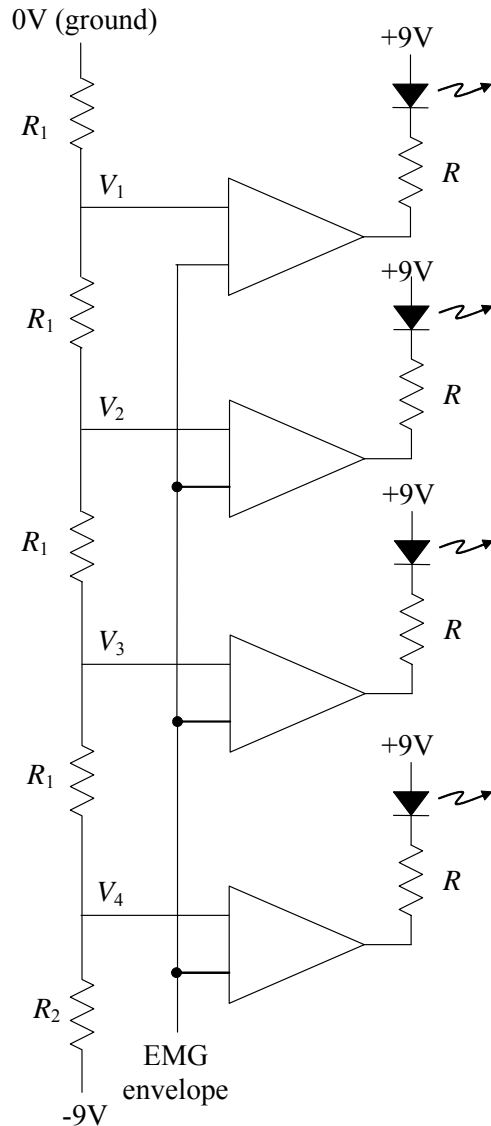
Note that the positive/negative terminal markers of the comparators have been omitted. You should figure out how to connect them for proper operation. The resistor ladder consists of four resistors of value R_1 and one resistor R_2. Derive expressions for V_1, V_2, V_3, and V_4 in terms of R_1 and R_2, for a -9V supply. (Assume that the comparators have zero current flowing into their input terminals.) Now build the circuit. A suggested value of R_1 is 1 kΩ. You may wish to make R_2 variable to allow for adjusting the threshold levels.

Connect this circuit to your EMG envelope circuit, and test the circuit using a sine wave of varying amplitude. Observe the important waveforms within the circuit.

- Demonstrate the operation of this circuit to your T.A. using a sine wave input (20 points).

Now for fun, try the complete system with an EMG input, and test your strength!

NOTE: A flash A/D converter works using a resistor ladder and a string of comparators just as we have built in this lab. The only thing we didn't build is some combinational digital logic to convert the "thermometer code" (N steps coded using N wires) we use to drive the LEDs into a traditional binary code (N steps coded using $\log_2(N)$ wires).

At this point, you may disassemble the LED bar-graph circuit if you are running out of space on your breadboard for the circuits in Section IV. However, you are encouraged to keep it running so you have simultaneous LED and audio outputs from your circuit.

Part IV: Voltage-Controlled Oscillator for Audio Output

In the final section of this lab, we will add an audio output to our EMG system. We will build a *voltage-controlled oscillator* to drive a speaker with a tone whose frequency increases with EMG strength. Before beginning this section, you should have read Sections 2.8.2 ("The Inverting Integrator"), 13.4 ("Bistable Multivibrators"), and 13.5 ("Generation of Square and Triangular Waveforms Using Astable Multivibrators") in Sedra and Smith, 5th edition.

Let's begin by reviewing the circuit shown Fig. 2.39(a) in the book. This circuit is an *ideal integrator*, which means that its output is the time integral of its input (with a negative sign added, as showing in equation 2.49). From basic calculus, if we apply a constant negative voltage $v_I (t) = -V$, then the output will be $v_O(t) = (V/RC)t$. In other words, the output voltage will increase linearly over time. The math indicates that the output voltage will keep on going to infinity if we wait long enough, but of course that doesn't happen in real circuits; the output just goes as high as the op amp can drive it (usually one or two volts below the positive power supply), and then the circuit no longer works as an integrator.

The behavior of this circuit is easy to understand if you remember two basic principles you learned long ago: (1) thanks to negative feedback, the negative terminal of the op amp is held at a virtual ground, so the current through the resistor is just v_I /R, and (2) if we have a current I flowing onto a capacitor C, then the voltage across the capacitor changes as $dV/dt = I/C$.

In isolation, an ideal integrator is not a particularly useful circuit since its output tends to be driven to one of the power supply rails rather quickly. However, it can be very useful if we provide some feedback to keep the output away from either extreme. For this task, we will use a *hysteretic comparator*. You are already familiar with the basic operation of a comparator from Part III of this lab. The concept of hysteresis is explained in Section 13.4; we will be using the circuit shown in Fig. 13.20, which uses *positive* feedback. It can be built either with an op-amp (such as the LM324) or a comparator. (If you use an op-amp, note that the output levels may not reach the power supplies. Most unless you use a *rail-to-rail op amp,* the output can typically swing only within 1-2 V of the power

supply. The LM324 is optimized for single power supply operation, which means that its output can swing very close to the negative power supply, but not that close to the positive power supply. You are encouraged to test your op amp and measure its limiting output voltages L_+ and L_-.)

Build the hysteretic comparator shown below. Use $R_1 = 10$ kΩ and $R_2 = 33$ kΩ. Apply a large-amplitude (± 9V), 1-kHz triangle wave to the input. Observe both the input and output simultaneously on a scope. Find the minimum and maximum output levels (L_+ and L_-) and the threshold levels (V_{TL} and V_{TH}). Do your threshold values match those predicted by equations 13.29 and 13.30?
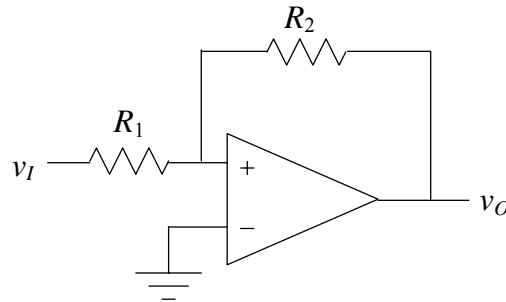

- Demonstrate the operation of this circuit to your T.A., and report your values of L_+, L_-, V_{TL}, V_{TH} (10 points).

The voltage-controlled oscillator (VCO) we will build is shown below. It is similar (but not identical) to the circuit shown in Fig. 13.25(a) in your book.
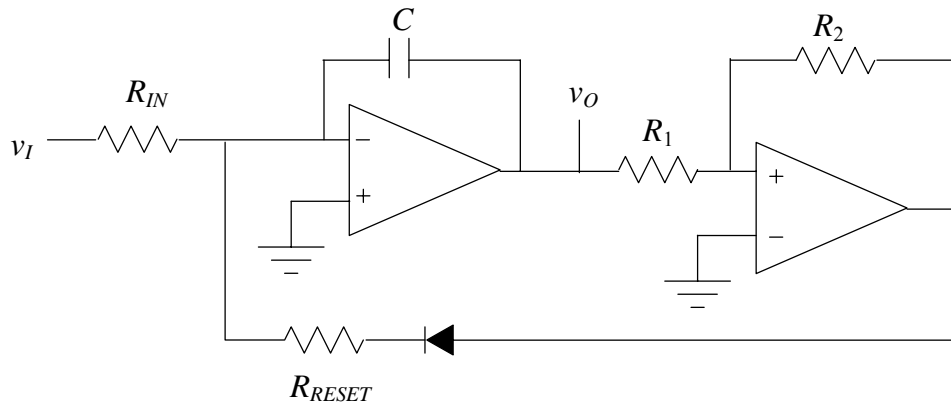
Use an LM324 for the integrator op amp (and for the hysteretic comparator, if you wish), and a 1N4148 for the diode. Start with a value of 1000 pF for C. This circuit can be configured to generate waveforms that look something like this at v_O:
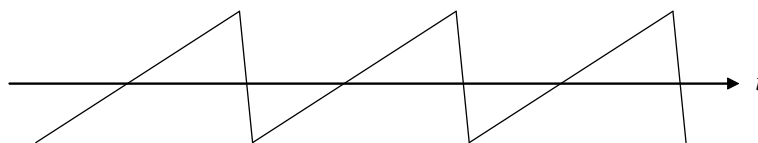
The operation of the circuit is as follows: Assume that v_I is always a negative voltage (like the output of our EMG envelope detector). When the output of the comparator is negative, the diode prevents any current from flowing through R_{RESET}. In this case, the integrator (whose output is v_O) charges upwards with a slope of $v_I /(R_{IN}C)$. When v_O exceeds V_{TH} of the hysteretic comparator, the comparators output goes high. This forward biases the diode, and (if R_{RESET} is much smaller than R_{IN}) causes the integrator to slew negative very quickly (at a rate determined by L_+ and R_{RESET}). When the integrator output drops below V_{TL}, the comparator output goes low, and the process repeats itself.

Since the upward-going slope is dependent on v_I, as v_I gets more negative, the frequency of the oscillation will increase.

We would like to design this circuit to produce tones in the middle of the audio range for typical EMG envelopes, around 200 Hz – 1400 Hz, roughly. (The "middle C" on a piano keyboard is 278 Hz.) Select values of R_{IN} and R_{RESET} to give audio frequencies for typical EMG envelope outputs (as recorded by you in Part II). Make $R_{RESET} \ll R_{IN}$ so that the downward slope is almost vertical. Build the VCO circuit, and test it. You may wish to test it first with a negative voltage input provided by a power supply or a potentiometer, or you can hook it straight up to your EMG envelope output.

Now, connect a small speaker or headphones to your circuit, using a series capacitor to prevent dc current from passing through the speaker. Use a small-valued resistor to limit the current (and hence volume):
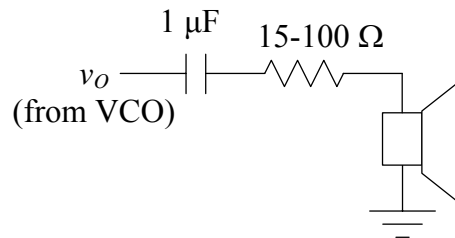
You should hear a steady tone whose pitch increases as you contract your muscle. Feel free to adjust component values to get a nice frequency range.

- Demonstrate the operation of this circuit to your T.A. (20 points).