LABORATORY PROJECT NO. 1
DESIGN OF A MYOGRAM CIRCUIT

1. INTRODUCTION

1.1. Electromyograms

The gross muscle groups (e.g., biceps) in the human body are actually composed of a large number of parallel fiber bundles functionally arranged into individual motor units. When each motor unit is activated by nerve commands, (action potentials), from the central nervous system, actuating electrical impulses propagate down the length of the fibers that make up the unit. Two neighboring electrodes placed on the skin's surface near the muscle will pick up differential voltages in the fringe regions of these electrical impulses--a plot of these voltages is called an *electromyogram*, or EMG ("myo" is a root meaning "muscle"). The strength of the voltage at the skin surface is very small, however, on the order of 10's of microvolts, and therefore amplification is required before recording the EMG or displaying the EMG on an oscilloscope. A third electrode, called the reference electrode, is placed away from the muscle; this allows any common-mode voltages (noise picked up from nearby electrical equipment, for example) to be subtracted and therefore ignored. Fig. 1 illustrates the system for measuring an EMG.

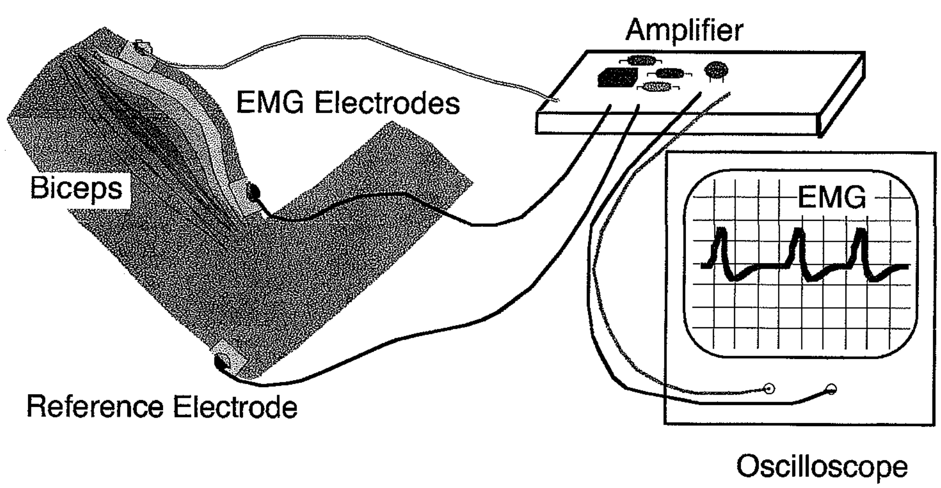


Fig. 1. System for measuring an electromyogram.

When only slight force generation is required, only one or a few motor units will be excited and the resulting EMG is comprised of a series of seemingly random spikes, with the time between spikes on the order of a few milliseconds. As more force is needed, more motor units will be simultaneously recruited and their spikes will be incoherently superimposed on those of other activated units. The frequency of the spikes from each unit will increase also, resulting in a complex, busy pattern to the EMG from a muscle group that is generating considerable force.

EMG studies are useful for assessing the health of the neuromuscular system, since certain diseases such as multiple sclerosis slow down or even suppress normal nerve and muscle firing. In addition, several research groups have recently studied the possibility of using EMG signals to control artificial limbs for patients who have lost an extremity; the EMG signal would be obtained from a surviving portion of the limb and would represent the patient's central nervous system's desire to move the limb in a certain direction with a certain force.

1.2. The Design Project

Your project is to design an amplifier circuit for measuring EMG's. The circuit will consist of resistors, operational amplifiers (or op-amps), two 9 Volt batteries, battery clips, wires, a protoboard, and electrodes. The total parts cost, excluding the batteries and protoboard, which you will use for several laboratory exercises, is around ten dollars. For your convenience the needed parts are available from the EE stockroom, but you may purchase them elsewhere if you like.

The circuit for measuring EMG's is shown in Fig. 2. The electrodes are attached to the biceps on the upper arm where they pick up tiny voltages generated by nerves and muscle. Because the power in these signals is minute, attaching the electrodes directly to a circuit that draws more than an infinitesimal current causes the voltage to drop to almost zero. The solution to this dilemma is to use pre-amps that draw approximately zero current from the electrodes while outputting the same tiny voltages as the electrodes at a much higher current level. The pre-amp is followed by a differential amplifier that measures the difference between the electrode voltages and multiplies that difference by five hundred. We use a differential amplifier because it eliminates any noise voltage from external sources that is common to both electrode signals.

In this laboratory exercise, you will design the pre-amps and choose resistor values for the differential amplifier. First, to help you understand the operational amplifier and Kirchhoff's laws, you will construct circuits consisting of only resistors and voltage sources. You will measure the circuits and plot the results. Then you will derive a gain formula that explains the plot, and you will choose a pre-amp circuit design that increases the drive capability of the electrode signal without drawing appreciable current. Second, you will choose resistor values for the differential amplifier so that it multiplies the difference in the electrode voltages. Third, you will use the completed circuit to measure your myogram signals with the help of an oscilloscope. In this phase of the project, you will also use LabView® and Matlab® to capture and analyze data. Fourth, you will write a formal report on your measurements of actual EMG's.

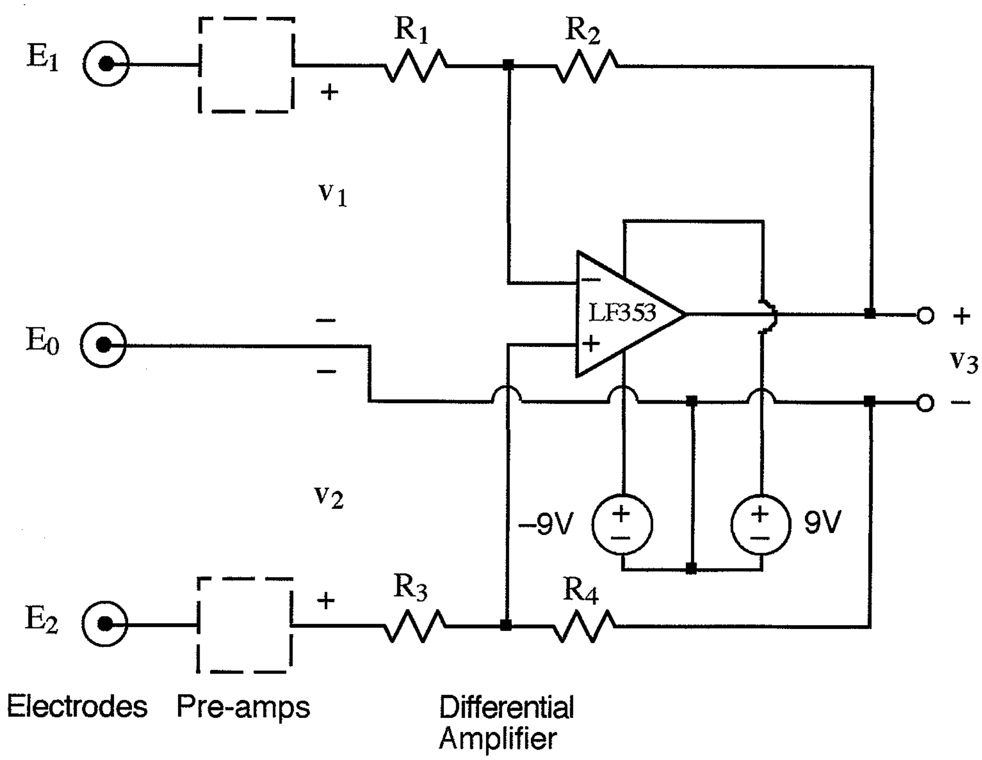


Fig. 2. Schematic Diagram of the electromyogram circuit.

2. ANALYZE OP-AMP CIRCUITS

2.1. Op-amp Circuits: v_o vs R_f measurements

The purpose of this portion of the laboratory exercise is to reveal the behavior of basic op-amp circuits with the aim of finding a circuit suitable for use as a pre-amp circuit. You will analyze two different commonly used op-amp circuits: a negative-gain amplifier and a positive gain amplifier. Afterwards, you will decide which circuit is capable of sensing the weak EMG signals from electrodes without loading them down. We begin with a discussion of op-amps but find that we may replace the op-amp with a power supply adjusted by hand. This reduces the analysis of op-amp circuits to an exercise in the use of Kirchhoff's laws.

Fig. 3 shows a symbolic representation of an op-amp. The output of the op-amp acts like a dependent voltage source whose output voltage depends on the voltage drop that it measures across its input terminals that are labeled + and – to indicate the polarity of the measurement. The LF353 op-amp we use in this experiment is packaged as an integrated circuit (IC) in an 8-pin package. The op-amp IC requires two power-supply connections shown in Fig. 2 but omitted from Fig. 3 for clarity. These power-supply connections are the source of power for creating v_o, and one may think of the op-amp as routing either the positive or negative power-supply to the output, v_o.

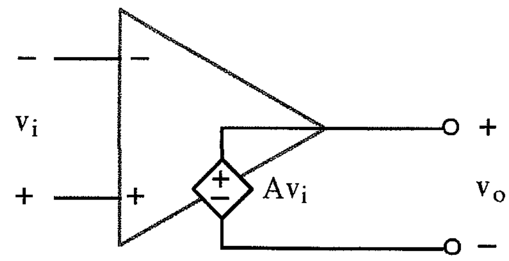


Fig. 3. Op-amp modeled as dependent voltage source.

Inside the IC, there are many transistors and other components that you will study in detail in future courses, but the net effect of all this circuitry is to create an output voltage that is 10^5 or more times the size of the voltage drop across the + and – input terminals:

$$v_o = Av_i \tag{1}$$

where

A is the gain (approximately 10^5)

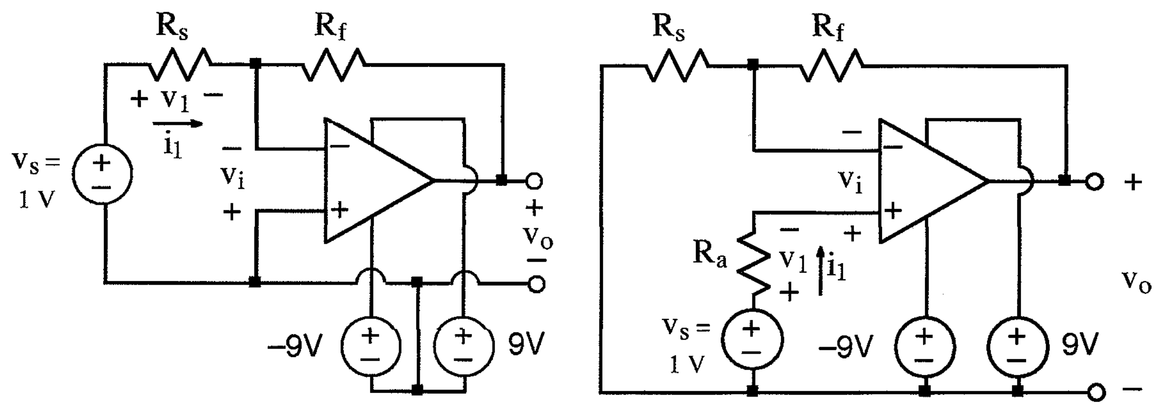
v_i is the voltage drop measured from the + input to the – input

v_o is the voltage drop measured from the op-amp output to reference

Any nonzero voltage v_i causes the op-amp output to be huge, owing to the high gain, A. When a resistor connects the op-amp output to the – input, the op-amp output voltage tends to pull the voltage at the – input in a direction that reduces v_i. This is called *negative feedback*, meaning that the output of the output of the op-amp is acting to negate any voltage difference that arises across the + and – inputs of the op-amp. Although a tiny voltage difference remains in practice, a good model of the op-amp circuit is that $v_i = 0$ and that v_o has whatever value is necessary to make $v_i = 0$. This behavior allows one to design circuits that amplify signals and increase their current-drive capability.

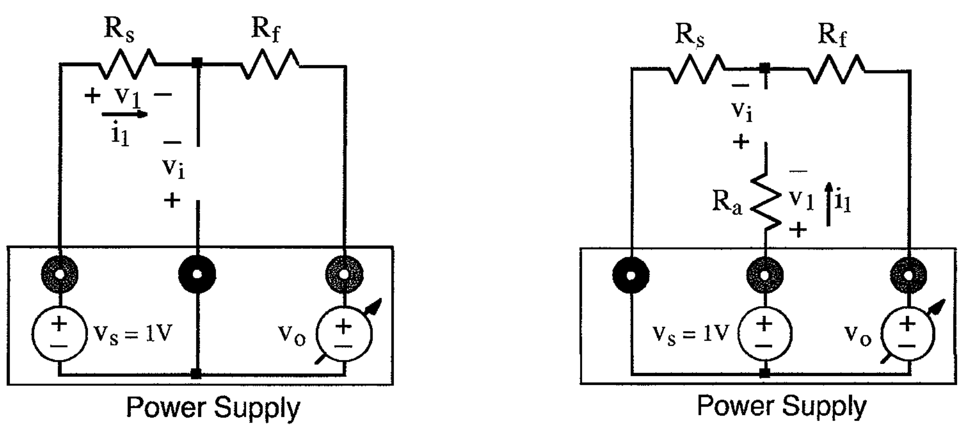
It also happens that almost no current flows into the + and – inputs of the op-amp—as though the op-amp were absent. Consequently, in a circuit with negative feedback, we may analyze the behavior of the op-amp by removing it from the circuit entirely and replacing it with a voltage source, called v_o, that is adjusted until the voltage drop measured across the + and – inputs equals zero. In other words, we replace the dependent voltage source in the op-amp with a power supply whose voltage we adjust by hand until the voltage drop across the + and – inputs equals zero. We employ this method of analysis because the resulting circuit is simple enough that we may solve it using a few equations resulting from Kirchhoff's laws. Later on, we will use the op–amp again, allowing it to produce the output voltage, v_o, automatically.

Fig. 4 shows two op-amp circuits that you will analyze using only resistors and an adjustable voltage source (or power supply), as shown in Fig. 5. Construct the circuit in Fig. 5 on a protoboard, as shown in Fig. 6. You will need five resistors: two 10 kΩ, two 20 kΩ, and one 30 kΩ. The power supplies at your lab bench will act like the voltage sources. Fig. 6 shows how to connect the power supply. Note how the voltage sources are connected *inside* the power supply. The controls on the power supply allow you to precisely adjust the voltages of these sources.



(a) (b)

Fig. 4. Simple op-amp circuits: (a) Negative-gain circuit, (b) Positive-gain circuit.



(a) (b)

Fig. 5. Circuits for modeling op-amp circuits: (a) Negative-gain op-amp circuit, (b) Positive-gain op-amp circuit.

For R_s, use a 20 kΩ resistor. For R_a in (b), use a 10 kΩ resistor. For R_f, use each of the following resistor values in turn: 0 Ω (a wire), 10 kΩ, 20 kΩ, and 30 kΩ. Using a Ohmmeter, measure each resistance and record the value before using it in the circuits. For v_s, use the power supply controls to set the output of the 6V supply to +1.00 V. Use a digital meter on the lab bench to measure the voltage drop, v_i. For each value of R_f, adjust the output of the 25V supply representing v_o until $v_i = 0$. Record the value of v_o from the power supply display. Also, record the value of the voltage drop, v_1, across R_s or R_a as appropriate, being careful to use the proper polarity as shown in Fig. 5. (The values of v_1 will be used later on to find the input resistance of the circuits.) Repeat the entire experiment for both circuits. (You will need a negative

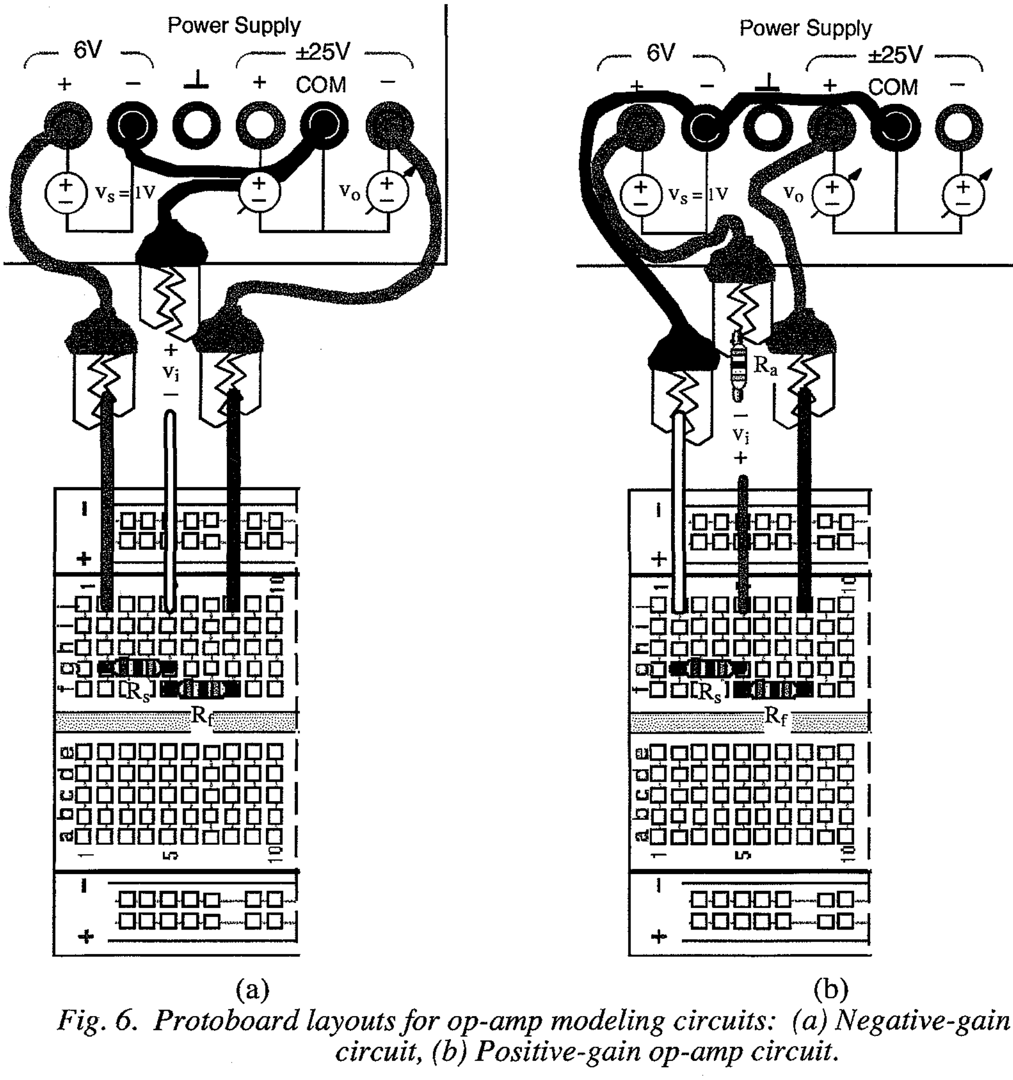


Fig. 6. Protoboard layouts for op-amp modeling circuits: (a) Negative-gain op-amp circuit, (b) Positive-gain op-amp circuit.

voltage for v_o for the circuit in (a) and a positive voltage for v_o for the circuit in (b). Fig. 6 shows the necessary power-supply connections.) In your lab notebook, record all pertinent data from the experiments. This includes circuit diagrams, measured resistances of R_a, R_s, and R_f, and values of v_o and v_1.

2.2. Op-amp Circuits: plot of $y = v_o/v_s$ vs $x = R_f/R_s$

Using the data you have recorded and a piece of graph paper, make a plot *by hand* of $y = v_o/v_s$ versus $x = R_f/R_s$ for each op-amp circuit. That is, calculate the value of v_o/v_s and R_f/R_s for each measurement. Then plot these values as the y and x coordinates of data points. After plotting the data points, use a ruler to draw straight lines that are the best fit to the four data points on each plot.

2.3. Op-amp Circuits: equation for straight line fit

Write down equations for your straight line fits for the plots of $y = v_o/v_s$ vs $x = R_f/R_s$ for both op-amp circuits. That is, estimate the values of a and b in the equation for each straight line:

$$y = ax + b \qquad (2)$$

2.4. Op-amp Circuits: Matlab® `polyfit` coefficients

Using your measured data and the `polyfit` in Matlab®, find a linear, (i.e., polynomial of order 1), equation for $y = v_o/v_s$ versus $x = R_f/R_s$ for each op-amp circuit. See code from `polyfit_diode.m` in the Pseudo-Laboratory Project handout for an example of how to perform this task.

2.5. Op-amp Circuits: expression for v_o

Using Kirchhoff's laws and Ohm's law, analyze each op-amp circuit in Fig. 5 and derive an equation for $y = v_o/v_s$ versus $x = R_f/R_s$. Hint: first, solve for v_o versus v_s by assuming $v_i = 0$ V, and using voltage loops that include v_i. Comment in your notebook on how similar the results are for the three methods of finding a straight-line fit.

2.6. Op-amp Circuits: expression for input resistance

The input resistance of a circuit is the resistance that, when placed directly across v_s, would draw the same current from v_s as the entire actual circuit. By Ohm's law, the input resistance is equal to v_s divided by the current, i_1, flowing out of the v_s source:

$$R_{in} \equiv \frac{v_s}{i_1} \qquad (3)$$

It is somewhat inconvenient to measure current i_1 directly, as the current meter must be inserted in the circuit so that the current from the v_s source flows through it. To avoid this inconvenience, we determine i_1 by measuring the voltage drop across a resistor in series with the v_s source and using Ohm's law to find the current. Use this idea and Kirchhoff's laws to find a symbolic expression for the input resistance, R_{in}, as a function of resistance values for each circuit.

2.7. Op-amp Circuits: measured input resistance

Using $v_s = +1.00$ V (or whatever actual value of v_s you used) and your measured values of i_1 from earlier, calculate the measured input resistance, R_{in}, of each configuration of each circuit. Make a table listing the values of R_f, the values of R_{in} calculated from your symbolic formulae and measured resistor values, and the values of R_{in} calculated from v_s and i_1 values. Extremely high values of input resistance are desirable for the pre-amps, as this means the electrode is driving an open circuit, and this requires zero power.

3. DESIGN, CONSTRUCT, AND TEST PRE-AMPS

3.1. Pre-amp: design

Based on the above results and analysis, design a pre-amp for the electromyogram circuit. (The final circuit will have two identical pre-amps.) The design objectives for the pre-amp are twofold:

i. $R_{in} = \infty\ \Omega$

ii. $v_o/v_s = 1$ (gain of unity)

Eliminate unnecessary components. Note that the design objectives yield a circuit that draws no current from the electrodes but outputs the electrode voltage. The op-amp circuit is thus a voltage follower. It is able to drive the differential amplifier that follows it.

3.2. Pre-amp: test results

Build the two identical pre-amp circuits on your protoboard using one LF353 op-amp integrated circuit. (The LF353 contains two op-amps in an 8-pin dual-in-line package.) See http://www.national.com/ds/LF/LF353.pdf for the pin numbers of the op-amp.

The LF353 requires a +9V and a –9V power supply connection for this laboratory exercise. When taking actual EMG measurements, you will use two 9V batteries to supply power, while testing the circuit, however, you may use a power supply connected as shown in Fig. 7. Be sure to connect the COM output, shown connected to a "rail" running down the side of the protoboard, to appropriate points in the circuit. How you lay out the remainder of the circuit on the protoboard is up to you.

Test the pre-amps by inputting various voltages and measuring the output voltages.

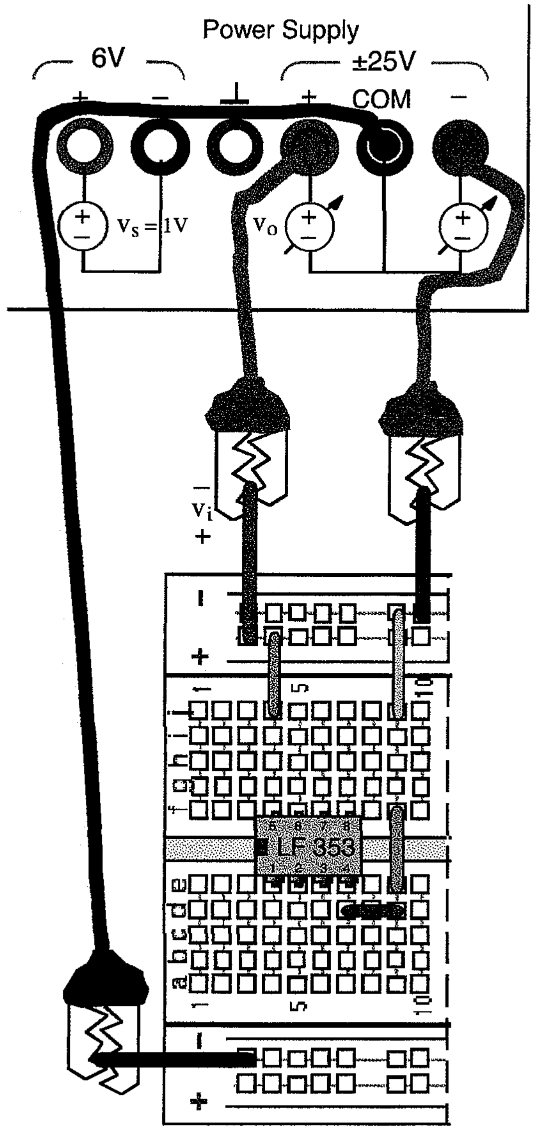


Fig. 7. Protoboard power-supply connection for powering op-amp.

4. DESIGN, CONSTRUCT, AND TEST DIFFERENTIAL AMPLIFIER

4.1. Differential Amplifier: expression for v_3

Using Kirchhoff's laws and Ohm's law, analyze the differential amplifier circuit shown in Fig. 2. Derive an equation for v_3 as a function of input voltages v_1 and v_2 and resistances R_1, R_2, R_3, and R_4.

4.2. Differential Amplifier: design

Based on the above analysis, design a differential amplifier for the electromyogram circuit. The design objectives for the differential amplifier are twofold:

i. v_3 must be proportional to *only the difference* between v_1 and v_2. (This means that any offset voltage common to both electrodes and arising from a source other than nerve and muscle activity will be canceled out.) Rewrite the formula for v_3 in terms the common mode signal, v_Σ, and the differential-mode signal, v_Δ, defined as follows:

$$v_\Sigma = v_1 + v_2, \qquad v_\Delta = v_1 - v_2.$$

Begin this process by making the following substitution:

$$v_1 = \frac{v_\Sigma + v_\Delta}{2}, \qquad v_2 = \frac{v_\Sigma - v_\Delta}{2}.$$

Show that v_3 is a function only of v_Σ if the ratio of R_1 to R_2 is the same as the ratio of R_3 to R_4. In other words, rewrite v_3 in terms of the following ratio, $\mathcal{R}$, and show that v_Δ disappears from the expression for v_3:

$$\mathcal{R} \equiv \frac{R_1}{R_2} = \frac{R_3}{R_4}$$

ii. The gain of the circuit *must* be 500. This makes the output as large as possible without causing the output to "saturate" by reaching the op-amp power supply voltages. (The output is limited by the power-supply voltages, resulting in clipping distortion in the output waveform if the voltage reaches the level of the power supply.)

iii. The input resistance for both inputs, (i.e., input voltage divided by input current), must be the same for both inputs (to help cancel out less than ideal output characteristics of the pre-amps).

iv. The input resistance for both inputs must be high enough that the input current never exceeds the maximum current, 10 mA, that the op-amp in the pre-amp can supply.

v. The maximum resistor value must be less than 1 MΩ to prevent noise currents from creating significant voltages across resistors.

4.3. Differential Amplifier: test results

Build the differential amplifier circuit. Test it by using voltage dividers to create small input voltages for the pre-amps. Measure the differential amplifier output voltages for several different pairs of input voltages. Make a table of the results.

4.4. Differential Amplifier: measured gain

Verify that the gain of the differential amplifier is close to 500. To calculate the gain, divide the change in output voltage, v_O, by the change in the difference input voltage, v_Δ. This method of calculating the gain eliminates a large constant offset in the output that results from an offset voltage across the + and – inputs. This offset voltage is only a few millivolts and represents the voltage across the + and – inputs that the op-amp interprets as exactly zero volts. In many applications this offset voltage may be neglected. In the differential amplifier circuit, however, the offset voltage is similar in size to the input signals and also gets multiplied by 500, causing a significant output voltage even when the two signals driving the differential amplifier are zero.

5. MEASURE ELECTROMYOGRAM

5.1. Plot of Electromyogram Waveform

Use two 9 V batteries as the power supplies for your electromyogram circuit.

Connect electrodes to your biceps—the muscle on the top of the upper arm that bulges when showing off your strength. Place two electrodes, measuring the voltages going into the preamps, about three inches apart, on the upper and lower end of the biceps slightly toward the outside of the muscle. Place the third, reference electrode, on the elbow. (Avoid placing the reference electrode on muscle.)

Connect the output of the electromyogram circuit to an oscilloscope. To eliminate the large constant vertical (DC) offset of the waveform, place a 0.1 μF capacitor between the differential amplifier output and the oscilloscope probe. That is, attach the oscilloscope probe to one side of the capacitor and connect the other side of the capacitor to the differential amplifier output. Observe the waveform on the oscilloscope and use LabView to capture an example of the waveform. Print out copies of the waveform for the lab notebook and report.

5.2. Matlab® Code and Calculation of Electromyogram Power

Write Matlab® code to calculate the average "power" of the recorded waveform by calculating the average value of voltage squared:

$$p = \frac{1}{N} \sum_{i=1}^{N} v_{3i}^2 \tag{4}$$

where

p is the average "power" of the output signal

N is the number of sample points

v_{3i} is the ith sample of the output voltage

(Note that p actually has units of voltage squared rather than power, but p is equal to the power we would have if we connected a 1 Ω resistor to the output of the circuit.)

5.3. Matlab® Code and Plot of Electromyogram Power vs Weight

Measure the average circuit output power, p, while holding the lower arm horizontal with no weight, one unit of weight, two units of weight, and three units of weight. Choose weights such that the three-unit weight requires significant but comfortable effort when held with the lower arm horizontal. When performing the tests with weights, keep your joints in a constant position as much as possible.

Using Matlab®, make a plot of p versus weight. Comment on the shape of this plot.

6. WRITE FORMAL REPORT

Write a formal report describing your work on this project. See instructions in "Course Procedures" about how to write the report. (Also, look for detailed point breakdowns for Lab 1 grading on the course web site.) Include at least the following in your report:

i. An abstract. The abstract is a one-paragraph succinct summary of the laboratory exercise. It should describe the key results of the experiments performed.

ii. A short introduction. You may attach this handout to the report in the appendix and refer to it so that you don't have to copy the information in it. Your introduction, however, must introduce your report and be unique to your report. The introduction gives the motivation for the experiments performed and describes the organization of the report.

iii. A careful description of the work that you did in Sections 2 through 5, above.

   a. Discuss and give appropriate quantitative results for each of the numbered subsections in Sections 2 through 5. Every subsection corresponds to a specific task with a specific quantitative result that must be described in your report. To facilitate grading, number the subsections of your report with the same numbers used in this handout.

   b. Give clear derivations of mathematical expressions, including explanations in words for every equation in every derivation. Include consistency checks of final results whenever possible.

   c. Explain how you chose the values of circuit components and include a schematic diagram showing component values for the final circuit.

   d. Explain all measurements carefully and include data appropriately in clearly labeled tables and graphs in the body of the report.

   e. Include listings of all your Matlab® programs in an appendix, and explain how the code works in comments.

   f. Show plots of your electromyogram and average circuit output power versus weight.

iv. A succinct conclusion. The conclusion must describe the overall performance of the circuit and list the most salient quantitative results of this laboratory project. As a guide to what the conclusion should say, consider what information would be most useful to a student about to start the lab.

Laboratory Notebook Grading

30		***Communication***
12		Student's work Reproducible from notebook
4		Written in Ink
4		Student Signed every page
4		Student Dated every page
6		TA Signature for every lab session (-3 each session missed)
44	**2.**	***Analysis of Op-Amp Circuits***
5		2.1. First op-amp circuit: v_o vs R_f measurements
5		2.2. Second op-amp circuit: v_o vs R_f measurements
4		2.3. First op-amp circuit: plot of $y = v_o/v_s$ vs $x = R_f/R_s$
4		2.4. Second op-amp circuit: plot of $y = v_o/v_s$ vs $x = R_f/R_s$
3		2.5. First op-amp circuit: equation for straight line fit
3		2.6. Second op-amp circuit: equation for straight line fit
3		2.7 First op-amp circuit: Matlab® `polyfit` coefficients
3		2.8 Second op-amp circuit: Matlab® `polyfit` coefficients
4		2.9. First op-amp circuit: expression for v_o
4		2.10. Second op-amp circuit: expression for v_o
3		2.11. First op-amp circuit: input resistance for circuit
3		2.12. Second op-amp circuit: input resistance for circuit
6	**3.**	***Design, Construction, and Testing of Pre-amps***
3		3.1 Pre-amp: design
3		3.2 Pre-amp: test results
10	**4.**	***Design, Construction, and Testing of Differential Amplifier***
4		4.1. Differential amplifier: expression for v_3
3		4.2 Differential amplifier: design
3		4.3 Differential amplifier: test results
10	**5.**	***Measurements of Electromyogram***
4		5.1. Plot of electromyogram waveform
3		5.2. Matlab® code and calculation of electromyogram power
3		5.3. Matlab® code and plot of electromyogram power vs weight

Report Grading

25		***Communication***
5		Clarity of style (ease of reading, and etc.)
4		Organization (ease of locating figures/code/etc)
4		English (grammar, punctuation, and etc.)
4		Section numbers and headings (use section numbers shown below)
4		Equations explained (at least one sentence between equations)
3		Figure titles and numbers
5		Matlab listings and comments (put in appendices)
5		***Abstract*** (succinct summary of numerical results)
5	**1.**	***Introduction*** (motivation for lab, overview of report organization)
36	**2.**	***Analysis of Op-Amp Circuits***
3		2.1. First op-amp circuit: v_o vs R_f measurements
3		2.2. Second op-amp circuit: v_o vs R_f measurements
3		2.3. First op-amp circuit: plot of $y = v_o/v_s$ vs $x = R_f/R_s$
3		2.4. Second op-amp circuit: plot of $y = v_o/v_s$ vs $x = R_f/R_s$
3		2.5. First op-amp circuit: equation for straight line fit
3		2.6. Second op-amp circuit: equation for straight line fit
3		2.7 First op-amp circuit: Matlab® `polyfit` coefficients
3		2.8 Second op-amp circuit: Matlab® `polyfit` coefficients
3		2.9. First op-amp circuit: expression for v_o
3		2.10. Second op-amp circuit: expression for v_o
3		2.11. First op-amp circuit: input resistance for circuit
3		2.12. Second op-amp circuit: input resistance for circuit
4	**3.**	***Design, Construction, and Testing of Pre-amps***
2		3.1 Pre-amp: design
2		3.2 Pre-amp: test results
10	**4.**	***Design, Construction, and Testing of Differential Amplifier***
4		4.1. Differential amplifier: expression for v_3
3		4.2 Differential amplifier: design
3		4.3 Differential amplifier: test results
10	**5.**	***Measurements of Electromyogram***
4		5.1. Plot of electromyogram waveform
3		5.2. Matlab® code and calculation of electromyogram power
3		5.3. Matlab® code and plot of electromyogram power vs weight
5	**6.**	***Conclusion*** (summary of key results, including numerical values)

LABORATORY PROJECT NO. 2
VISUAL PERCEPTION EXPERIMENTS

1. INTRODUCTION

1.1. Visual Perception

The input module of the human visual system is the eye (or oculus—Fig. 1), which has several important optical and neural functions. With its lens and curvature of the cornea, it focuses light from the outside world onto the back of the eye. The iris expands or contracts to control the amount of light collected. On the back surface of the eye is the light-sensitive nerve network of the retina.

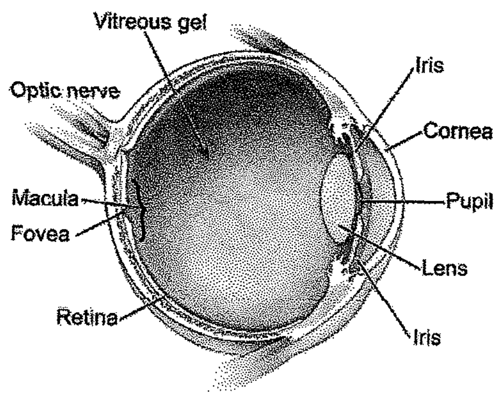


Fig. 1 – Anatomy of the eye (from the National Eye Institute/NIH).

The most important purpose of vision is to give spatial information about the outside world. Thus the region of the retina where the principle focus falls (the fovea in the macula) has a dense arrangement of cones to detect fine detail in the image about the particular portion of the scene the eye is directed to. The cones also give color perception. Progressively away from the fovea along the surface of the retina are found light rays from regions surrounding the region of interest—the *peripheral vision.* Here the cones give way to an increasing proportion of rods, which are very light sensitive but less densely packed, and the perception of spatial detail is much reduced in the periphery. (An engineering explanation of this arrangement is based upon the wise use of spatial bandwidth: employ large numbers of nerves where needed, but avoid excess nerve pathways where detail is less important.)

For time-varying images, different regions of the retina respond differently. For example, when a light is flashing at a low frequency, all parts of the retina will distinguish the individual flashes. As the frequency is increased, however, there is some frequency—the Critical Fusion Frequency, or CFF—at which the individual flashes are not noticeable and the illumination seems to 'fuse' into a steadily flowing perception. (This phenomenon makes moving pictures and TV, with their frames changing at a rate of about 60 per second, feasible.) The CFF for light focused on the human fovea is about 40-50 Hz, while the CFF for light focused on the peripheral retina is approximately half that value; there is considerable variation among subjects and depending upon the strength of the light source.

Even though they aren't well suited for fine spatial detail, the rods in the periphery still provide overall visual information to perception, e.g., locating objects within a broad field of view and giving the level of surrounding illumination. In addition—especially important to the survival of certain species of animals—the peripheral visual system can serve as an "early warning system" of attacks by predators as well as an adaptation designed for detecting moving prey. To accomplish these latter roles, the peripheral vision has developed the capability to detect *movement*, or motion of objects, in addition to seeing coarse stationary detail. Correspondingly, some of the nerve pathways in the outer portion of the retina are sensitive to time-varying events. (This is evident in certain animals: frogs are adept at catching fast-moving flies; horses are easily spooked by rapid movement.)

In imaging terms, movement is expressed as the time-rate-of-change of an object's position (velocity). Therefore, the nerves in the peripheral part of the retina can be considered, to some degree, to be *time differentiators* of spatial patterns. This is observed in nerve recordings from the so-called ON/OFF ganglion cells of the peripheral retina. This group of cells gets its name from the fact that they respond both when a test illumination is turned on *and* when the illumination is turned off; that is, they are sensitive to *temporal changes* in the illumination, not to the absolute state of the illumination. *In this lab, you will investigate the ability of your own peripheral vision to detect the time-rate-of-change of light patterns that you generate.*

1.2. The Design Project

Your project is to design a timing circuit that will cause an LED to flash at a controllable rate for visual discrimination experiments measuring fusion rate and peripheral perception. The circuit is an astable multivibrator driving an LED circuit, as shown in Fig. 2. Unlike op-amp circuits with negative feedback that operate in linear mode with input voltages approximately equal, this circuit operates in comparator mode with input voltages unequal. When the input voltages are unequal, the op-amp output is a large positive or negative voltage. The op-amp's power supply voltages (not shown on the schematic), minus small voltage drops occurring inside the op-amp, define the extremes of the output voltage. These extremes are referred to as "rail voltages," harking back to earlier times when circuits were often built between uninsulated wires, or rails, carrying power. The nature of the LED circuit in this laboratory exercise causes the op-amp output to swing back and forth between the rail voltages. In other words, the op-amp output is a square wave. This waveform is seen at the point labeled v_0 in Fig. 2.

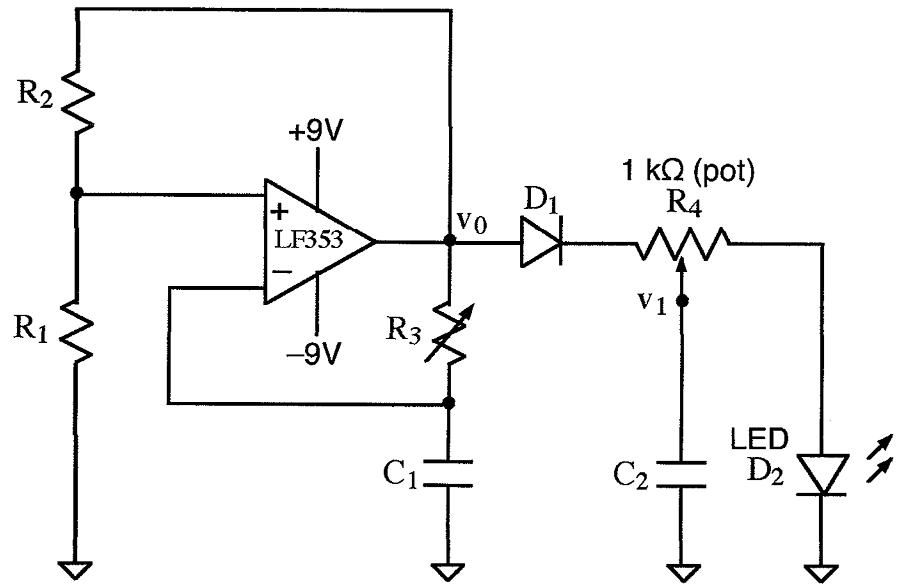


Fig. 2. Diagram of the timing circuit.

The square wave results from two sources. First, capacitor C_1 induces a difference between the + and – op-amp input voltages by effectively delaying the feedback signal from v_0 to the – input. Second, resistors R_1 and R_2 form a voltage divider, driven by v_0, that provides a changing reference voltage at the + input of the op-amp. The circuit has both negative and positive feedback. C_1 and R_3 provide negative feedback with op-amp output, v_0, changing in a direction that pulls the – input voltage toward the + input voltage. C_1 slows down this process, however, by slowly charging toward v_0. Eventually, however, the + input voltage and the – input voltage will be approximately equal. In a typical amplifier, v_0 would then reach an equilibrium value and remain constant. In this circuit, however, R_1 and R_2 provide positive feedback by feeding a portion of the change in v_0 back to the + input. The voltage at the + input drops as v_0 drops. This causes the op-amp input voltages to be different again, and that in turn causes v_0 to change polarity and swing all the way to the rail voltage. At this point, C_1 again charges toward the voltage at the + input and the entire process described above repeats with all signal polarities inverted. The reversals in v_0 continue indefinitely, with their timing being determined by resistor and capacitor values. Thus, the op-amp outputs a square wave.

The square wave drives an LED circuit whose purpose is to control the current flowing in the LED. The LED allows current to flow only in one direction, namely the direction that the "arrow" in the LED points. The LED also has a nonlinear current–versus–voltage response that lends itself to being modeled as a constant voltage drop when the LED is on and an open circuit when the LED is off. In other words, the LED behaves like a passive voltage source or an open circuit. You will determine the value of total resistance that will light the LED with the proper intensity for the fusion rate experiment. You will also determine the value of capacitance that will light the LED at a controlled rate for the peripheral vision experiment.

2. DESIGN ASTABLE MULTIVIBRATOR

2.1. Selection of R_1 and R_2

The astable multivibrator is the part of the circuit to the left of diode D_1. Your initial design problem is to choose component values for this part of the circuit.

First, we observe that with the op-amp operating as a comparator, the output voltage, v_o, is equal to $\pm V_{rail}$ where $+V_{rail}$ is the maximum possible v_o, and $-V_{rail}$ is the *minimum possible* v_o. ($+V_{rail} \approx$ positive supply voltage $-$ 1.1 V and $-V_{rail} \approx$ negative supply voltage + 1.3 V.) To simplify our analysis, we will assume $+V_{rail}$ = positive supply voltage = 9 V and $-V_{rail}$ = negative supply voltage = –9 V. (Since voltages that control timing for the most part scale with v_o, this assumption introduces only small errors.)

Second, we observe that the op-amp acts like either a positive or negative voltage source, with symmetrical timing for both. Thus, we may analyze the case of a positive voltage source and merely invert our results to account for the case of a negative voltage source.

Third, we observe that treating the op-amp as a voltage source means that we may analyze the circuit as three separate circuits, each driven by voltage source v_o, as shown in Fig. 3:

i. R_1 and R_2, (a voltage divider)
ii. R_3 and C_1, (an RC charging circuit)
iii. D_1, R_4, C_2, and LED (LED circuit)

Fourth, we observe that the length of time it takes C_1 to charge to the voltage set by the voltage divider is the length of time v_o stays positive. Thus, R_1 and R_2 set the trip point of the circuit, and R_3 and C_1 set the charging rate. To design the circuit, we first set the trip point by choosing the values of R_1 and R_2.

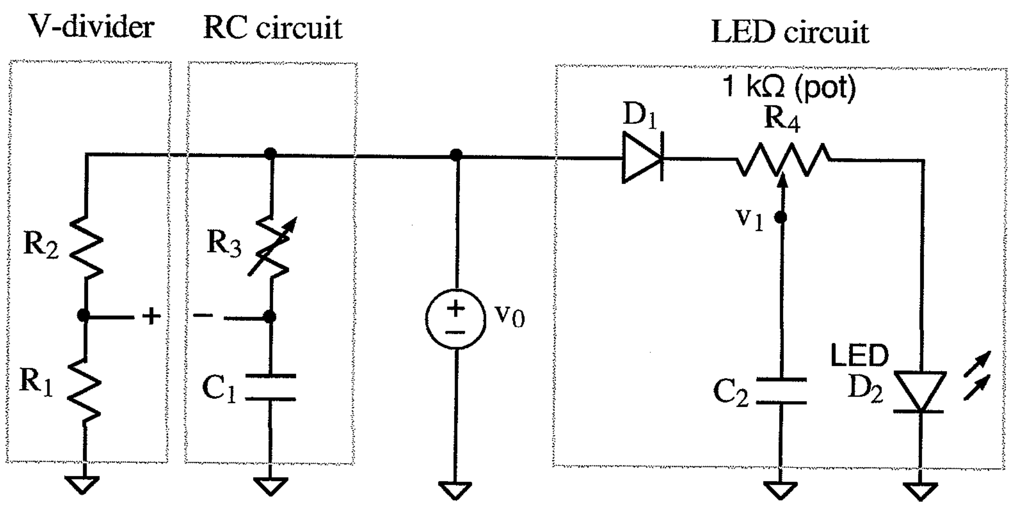


Fig. 3. Op-amp acting as voltage source driving three separate circuits.

Use the following design criteria (and solve appropriate voltage divider equations) to choose R_1 and R_2 values for the astable multivibrator part of the circuit:

i. Choose R_1 and R_2 to set the trip point, (i.e., the voltage at the + input), close enough to the rail voltage for v_o that as many time constants as possible elapse before the capacitor voltage at the – input charges up to the trip point.

ii. Choose R_1 and R_2 to set the trip point far enough from the rail voltage for v_o that the voltage at the – input, (i.e. across C_1), will reach the trip point even after being scaled down by 5 %. (This compensates for the addition of a scope probe at the – input that lowers the voltage at that point in the circuit, as noted in the discussion of the design for the peripheral vision experiment, below.)

iii. Choose R_1 and R_2 to limit the current through R_1 and R_2 to as small a value as possible so that the op-amp is able to drive other parts of the circuit without exceeding its maximum output current of approximately 10 mA. (The LED will use about 7 mA of current.)

iv. Choose R_1 and R_2 to avoid currents less than 10 μA so that noise currents remain small compared to signal currents.

2.2. Selection of R_3 and C_1

Use the following design criteria to choose R_3 and C_1 values for the astable multivibrator:

i. Choose C_1 to be 1 μF. (Since the voltage across it switches polarity, use a non-electrolytic capacitor for C_1.) This capacitor value allows us to use practical resistor values for square waves in the frequency range we require for our visual experiments.

ii. Choose R_3 to be a potentiometer that allows for the rate of the square wave at v_o to vary from 10 to 200 cycles per second. You will use this R_3 for the fusion frequency experiment. Note that one cycle of a square wave consists of a positive half and negative half, meaning it is *twice as long* as the time it takes for C_1 to charge to the set point. Also, note that the initial condition on C_1 will be the negative set point determined by R_1 and R_2, rather than 0 V, when v_o switches from negative to positive.

iii. Choose a second value of R_3 that causes the rate of the square wave at v_o to be 3 cycles per second. You will use this R_3 for the peripheral vision experiment later on.

3. CONSTRUCT AND TEST ASTABLE MULTIVIBRATOR

3.1. Measured Component Values

Obtain components for the circuit and measure the actual values of the resistors and capacitors. To use R_3 as a variable resistor, short the center tap to one side tap and connect to the side taps. Adjust R_3 to achieve a frequency of 200 cycles per second.

3.2. Square Wave Frequency

Construct the astable multivibrator circuit that you have designed and use an oscilloscope to determine the frequency of the square-wave output.

3.3. Predicted and Measured C_1 and v_o Waveforms

Store the v_o waveform from the oscilloscope and use Matlab® to make a plot superimposing the predicted and measured capacitor voltage and v_o waveforms. (Use actual component values for the predicted waveform.) Note any discrepancies and comment on possible causes.

3.4. Measured Value of R_4

Attach the LED circuit to the astable multivibrator but omit C_2. Without C_2, the potentiometer acts like a 1 kΩ resistor. Measure the actual resistance across the 1 kΩ potentiometer for later calculations. For D_1, use a 1N4148 diode.

3.5. Flashing LED Rate

Adjust R_3 in the astable multivibrator until the square wave slows down enough for the LED to appear as flashing rather than being continuously on. Using the oscilloscope, measure the actual rate for the square wave.

4. MEASURE VISUAL FUSION RATE

4.1. Critical Fusion Frequency

While watching the LED, slowly adjust R_3 until the flashing LED appears to be continuously on. This is the visual fusion frequency. Using the oscilloscope, measure the lowest rate of the square wave where the flashing appears to fuse. (The LED is actually only on half the time when the flashes fuse.)

4.2. LED Voltage

Referring to Fig. 4 below, adjust the R_4 potentiometer so that $R_{4left} = 800\ \Omega$ and add $C_2 = 0.1\ \mu F$ to the circuit. Measure the actual voltage, v_{LED}, across the LED when it is at its lowest value. (You will use this later on.)

4.3. LED Current

Using two oscilloscope probes, measure the voltage on both sides of R_4. Set the oscilloscope to measure the voltage drop across R_4 when the LED is on and, from this measurement, calculate the maximum current flowing in the LED when it is turned on. Verify that this value is less than the maximum rated value of 20 mA for the LED.

5. DESIGN AND CONSTRUCT LED CIRCUIT

5.1. Equations for v_1

The LED circuit, with C_2 included, controls how rapidly the LED current rises after it is turned on. For the peripheral vision experiment, using a current waveform that is differentiable makes tractable the mathematical analysis of peripheral vision, (see below).

Diode D_1 allows current to flow only in the direction of the arrow in the diode symbol. Consequently, D_1 looks like an open circuit when v_0 is negative. Being a silicon diode, D_1 looks like voltage drop, which may be modeled as a voltage source of approximately 0.7 V, when v_0 is positive. The LED is also a diode, but its voltage drop is approximately the value v_{LED} measured in Subsection 4.2 above. The presence of C_2 prevents the LED from turning completely off, allowing us to model it as a voltage source that is on all the time. Fig. 4 shows equivalent models for the LED circuit when v_0 is high and low. Both models are RC circuits, with the final conditions for one circuit being the initial conditions for the other as v_0 alternates between positive and negative values. By finding the Thevenin equivalent of the circuit to which C_2 is connected, we may solve each circuit in Fig. 4 as a simple RC circuit with a single voltage source.

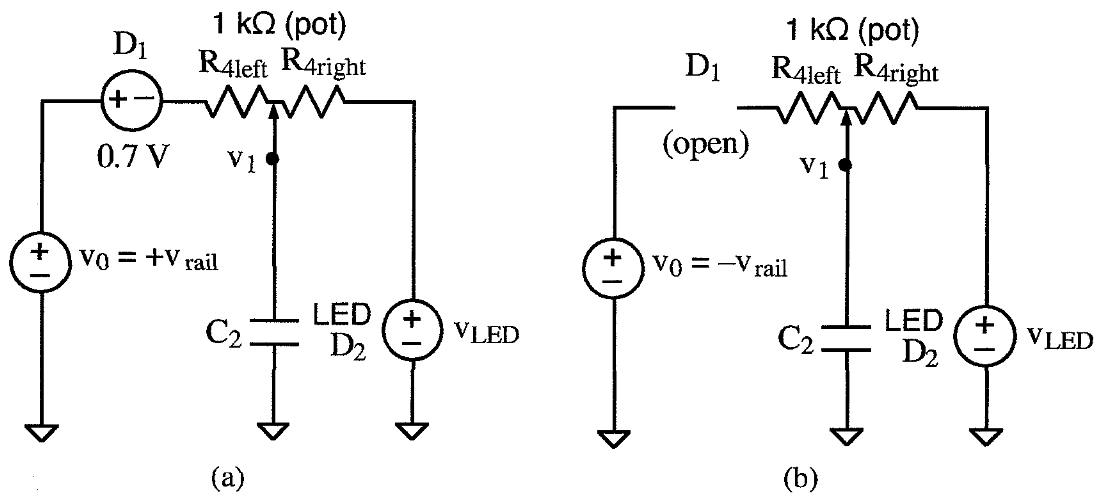


Fig. 4. Circuit models for LED circuit when v_0 *is high, (a), or low, (b).*

Derive symbolic equations for v_1 as a function of time for both of the circuits in Fig 4. Use the notation R_{4left} when referring to the left portion of potentiometer R_4, and R_{4right} when referring to the right portion of potentiometer R_4. Assume that the time constant for charging C_2 is short enough that v_1 reaches its final value before v_0 changes state in both circuits. For both equations for v_1, assume v_0 switches from low to high or high to low at time $t = 0$. In other words, reset the clock each time v_0 changes state.

5.3. Sketch of v_1 vs Time

Using the above results, sketch the waveforms for v_1 versus time starting when v_0 switches from $-V_{rail}$ to $+V_{rail}$ and from $+V_{rail}$ to $-V_{rail}$. Since the RC time constant is unknown at this point, this sketch may be drawn by hand and need only capture the shape of the charging and discharging curves and initial and final values of v_1.

5.4. Equation of i_{LED} vs Time

Because v_1 is easily measured in the circuit, the equations for v_1 are of interest. The brightness or luminosity of the LED depends on its current, i_{LED}, however. Using the circuits in Fig. 4, find equations for the current, i_{LED}, versus time starting when v_0 switches from $-V_{rail}$ to $+V_{rail}$ and from $+V_{rail}$ to $-V_{rail}$.

5.5. Potentiometer Setting

Adjusting the setting of the potentiometer changes the time constants for charging and discharging C_2. The design criteria result in a rapid but differentiable rise in the LED current, which we use in Section 6. Using your equations from Subsection 5.4 and the following assumptions and design criteria, determine the value of R_{4left} and R_{4right}:

i. The value of C_2 is exactly 0.1 μF.
ii. The total resistance of R_4 is exactly 1 kΩ.
iii. LED luminosity is directly proportional to LED current.
iv. After turning on, LED luminosity rises from 0 to 95 % of maximum, (i.e., 95 % of its final value), in 25 μs. (Hint: translate a 95 % change in current into an equivalent number of time constants.)
v. The maximum total current supplied by the op-amp must be less than 10 mA.

5.6. Plot of v_1 vs Time

Test the LED circuit by setting R_4 to its proper value and adding C_2. Record the value of R_{4left} and R_{4right}. Using LabView®, measure the voltage at v_1 and plot it versus time for 25 μs.

5.7. Plot of i_{LED} vs Time

Using Matlab® and the measured values of v_1, calculate and plot the value of i_{LED} versus time for 25 μs.

6. MEASURE AND ANALYZE PERIPHERAL VISUAL PERCEPTION

6.1. Perceived LED Flash Rate for Central Field of View

In your circuit, use the value of R_3 calculated in Subsection 2.2.iii, above. This should produce a flash rate of approximately 3.3 Hz. Look directly at the LED and visually determine the rate at which the LED flashes in units of cycles per second. It may be helpful to tap your finger at rate the LED appears to be flashing while someone else counts seconds.

6.2. Perceived LED Flash Rate for Peripheral Vision

Now position your head so the LED is in your peripheral vision, about 60° to the right or left of your line of sight. Determine the rate at which the LED appears to flash in units of cycles per second. Again, it may be helpful to tap your finger at rate the LED appears to be flashing. If necessary, adjust the angle of view to maximize the effect.

6.3. Sketch of Peripheral Vision Response Waveform

To understand the effect you have observed, consider the following mathematical expression that models how our peripheral vision responds to the intensity of light:

$$r = \left|\frac{dI}{dt}\right| \qquad (1)$$

where

r is the magnitude of the visual response

I is the intensity of light

t is time

This simple model expresses the idea that our peripheral vision responds to the magnitude of changes in light intensity as opposed to detailed patterns. Substitute i_{LED} for I in (1) and sketch the waveform for r. Count the cycles per second for r (i.e., the number of times per second that the signal rises and falls). Comment on how this compares with the result from Section 6.2.

7. WRITE FORMAL REPORT

Write a formal report describing your work on this project. See instructions in "Course Procedures" about how to write the report. (Also, look for detailed point breakdowns for Lab 2 grading on the course web site.) Include at least the following in your report:

i. An abstract. The abstract is a one paragraph succinct summary of the entire results. It should describe the key result of the experiments performed.

ii. A short introduction. You may attach this handout to the report in the appendix and refer to it so that you don't have to copy the information in it. Your introduction, however, must introduce your report and will be unique to your report. The introduction gives the motivation for the experiments performed and describes the organization of the report.

iii. A careful description of the work that you did in Sections 2 through 6, above.

   a. Discuss and give appropriate quantitative results for each of the numbered subsections in Sections 2 through 6. Every subsection corresponds to a specific task with a specific quantitative result that must be described in your report. To facilitate grading, number the subsections of your report with the same numbers used in this handout.

   b. Give clear derivations of mathematical expressions, including explanations in words for every equation in every derivation. Include consistency checks of final results whenever possible.

   c. Explain how you chose the values of circuit components and include a schematic diagram showing component values for the final circuit.

   d. Explain all measurements carefully and include data appropriately in clearly labeled tables and graphs in the body of the report.

e. Include listings of all your Matlab® programs in an appendix, and explain how the code works in comments.

f. Show plots of your astable multivibrator output, the voltage across the capacitor in the LED circuit, and the current in the LED.

g. List the visual fusion rate and peripheral perceived flashing rate that you measured.

iv. A succinct conclusion. The conclusion must list the most salient quantitative results of this laboratory project. As a guide to what the conclusion should say, consider what information would be most useful to a student about to start the lab.

LABORATORY PROJECT NO. 2
Laboratory Notebook Grading

THE UNIVERSITY OF UTAH

30		***Communication***
12		Student's work Reproducible from notebook
4		Written in Ink
4		Student Signed every page
4		Student Dated every page
6		TA Signature for every lab session (-3 each session missed)
10	**2.**	***Design of the Astable Multivibrator***
5		2.1. Selection of R_1 and R_2
5		2.2. Selection of R_3 and C_1
20	**3.**	***Construction and Testing of Astable Multivibrator***
3		3.1 Measured Component Values
3		3.2 Square Wave Frequency
8		3.3. Predicted and Measured C_1 and v_o Waveforms
3		3.4. Measured Value of R_4
3		3.5. Flashing LED Rate
10	**4.**	***Measurement of Visual Fusion Rate***
4		4.1. Critical Fusion Frequency
3		4.2 LED Voltage
3		4.3 LED Current
20	**5.**	***Design and Construction of LED Circuit***
4		5.1. Equation for v_1 Before LED Turns On
3		5.2. Equation for v_1 After LED Turns On
3		5.3. Sketch of v_1 vs Time
3		5.4. Sketch of i_{LED} vs Time
3		5.5. Calculation of Potentiometer Setting
2		5.6. Plot of v_1 vs Time
2		5.7. Plot of i_{LED} vs Time
10	**6.**	***Measurement and Analysis of Peripheral Visual Perception***
4		6.1. Perceived LED Flash Rate for Central Field of View
3		6.2. Perceived LED Flash Rate for Peripheral Vision
3		6.3. Sketch of Peripheral Vision Response Waveform

ECE 1270 LABORATORY PROJECT NO. 2

Report Grading

THE UNIVERSITY OF UTAH

25		***Communication***
5		Clarity of style (ease of reading, and etc.)
4		Organization (ease of locating figures/code/etc)
4		English (grammar, punctuation, and etc.)
4		Section numbers and headings (use section numbers shown below)
4		Equations explained (at least one sentence between equations)
3		Figure titles and numbers
5		Matlab listings and comments (put in appendices)
5		***Abstract*** (succinct summary of numerical results)
5	**1.**	***Introduction*** (motivation for lab, overview of report organization)
10	**2.**	***Design of the Astable Multivibrator***
5		2.1. Selection of R_1 and R_2
5		2.2. Selection of R_3 and C_1
15	**3.**	***Construction and Testing of Astable Multivibrator***
3		3.1 Measured Component Values
3		3.2 Square Wave Frequency
4		3.3. Predicted and Measured C_1 and v_o Waveforms
3		3.4. Measured Value of R_4
2		3.5. Flashing LED Rate
10	**4.**	***Measurement of Visual Fusion Rate***
4		4.1. Critical Fusion Frequency
3		4.2 LED Voltage
3		4.3 LED Current
15	**5.**	***Design and Construction of LED Circuit***
2		5.1. Equation for v_1 Before LED Turns On
2		5.2. Equation for v_1 After LED Turns On
3		5.3. Sketch of v_1 vs Time
3		5.4. Sketch of i_{LED} vs Time
2		5.5. Calculation of Potentiometer Setting
1		5.6. Plot of v_1 vs Time
2		5.7. Plot of i_{LED} vs Time
10	**6.**	***Measurement and Analysis of Peripheral Visual Perception***
4		6.1. Perceived LED Flash Rate for Central Field of View
3		6.2. Perceived LED Flash Rate for Peripheral Vision
3		6.3. Sketch of Peripheral Vision Response Waveform
5	**6.**	***Conclusion*** (summary of key results, including numerical values)

ECE 1270 LABORATORY PROJECT NO. 3

A MODEL OF TISSUE IMPEDANCE

THE UNIVERSITY OF UTAH

1. INTRODUCTION

1.1. Electromyograms

Modern humans are *immersed in* an environment filled with a background of electromagnetic radiation. Some of the sources are very low in public exposure intensity (TV, radio and other communication stations; 60-Hz power lines), some are of moderate intensity (cell phones when placed against the head), and some are intentionally strong (MRI imagers; radio-frequency tissue ablation for cancer treatment). Around the world, many research teams are studying how exposure to this electromagnetic radiation affects the body, and therefore are interested in modeling the electrical properties of tissue.

Cells are the building blocks of the tissues of the body, and various types and sizes of cells make up a large proportion of the body's volume. A single cell (Fig. 1A) can be viewed as a fluid-like substance with several species of mobile ions (the cytoplasm) contained within a semi-permeable cell wall (the cell membrane). Outside the cell is more fluid (the extracellular fluid), with again several species of mobile ions. Electrically, the cytoplasm can be modeled to first order as a conductive medium—due to the presence of the large concentrations of ions—characterized by a given value of conductivity, σ, (or its inverse, resistivity, ρ). The extracellular fluid can also be modeled as a conductive medium. The cell wall, on the other hand, is relatively insulating and, since it is a thin layer, is modeled as a capacitive medium with a given relative permittivity ε_r.

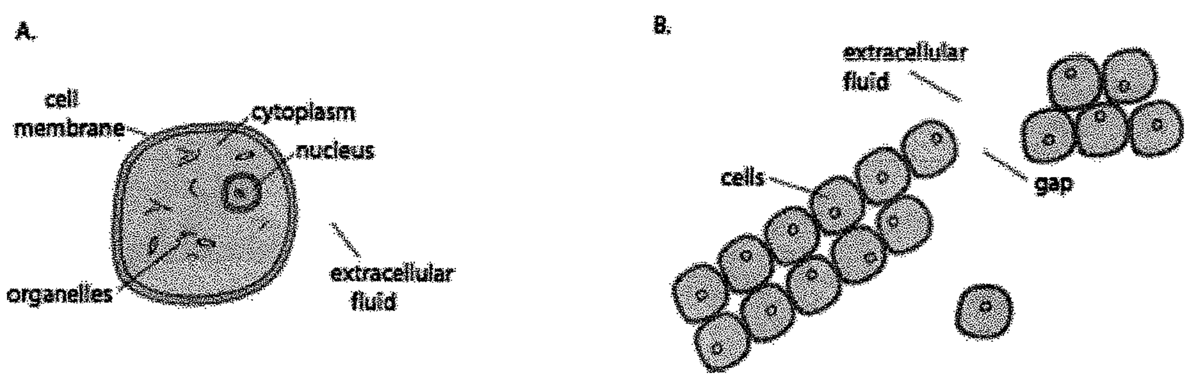


Fig. 1 A) Simplified diagram of a single cell, whose size can vary between 10 µm to nearly 1 mm; B) Tissue is composed of collections of cells. Gaps between the cells allow current to flow through shunt paths.

Tissues are composed of arrangements of cells (Fig. 1B) surrounded by the conductive extracellular fluid. In some places, the cells are tightly bound together and any circulating current must pass through the cell membranes. In other places, there are gaps (shunt paths) through which current can flow.

With cells in mind, consider a region of the body where there is a volume of soft tissue (muscle and fat) covered by skin upon which two opposing electrodes can be attached (e.g., the biceps muscles of the upper arm). A simple equivalent electrical model of the tissue between the two electrodes is shown in Fig. 2A. This is a lumped-element model where all inner-tissue cells are combined together into a single series R_cC_c branch. This branch in turn is in parallel with a resistive branch, R_t, representing the shunt intracellular fluid paths. At both ends of this circuit are parallel R_SC_S segments representing the electrical properties of the thin skin directly underneath the electrodes.

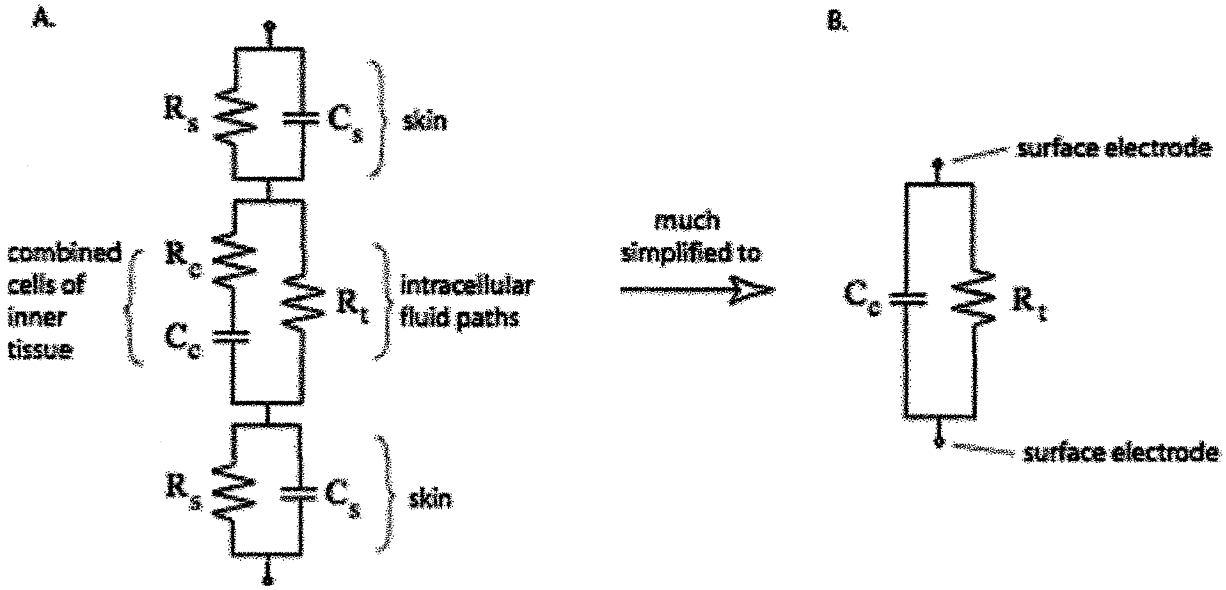


Fig. 2 – A) Lumped-element model of the electrical behavior of tissue bordered by skin; B) After several simplifications, the model reduces to its essence, a parallel RC circuit.

With some reasonable assumptions, this model can be greatly simplified. Assume that the combined resistance of the cell cytoplasm, R_c, is much lower than the reactance, $1/\omega C_c$, due to the cell membranes. Also, assume that the resistance of the thin skin, R_S, is much lower than both the skin reactance, $1/\omega C_S$, and the tissue resistance, R_t. (The validity of these assumptions depends very much upon the particular tissue region being modeled and the frequency of the electrical excitation, but for muscle and skin at a relatively low frequency of 25 kHz, these approximations are appropriate.) Then the model of Fig. 2A reduces to the simple R_tC_c parallel equivalent circuit shown in Fig. 2B. In the laboratory exercise detailed below, you will make measurements with the aim of finding typical values for the parameters of this simplified circuit.

1.2. The Design Project

Your project is to design an oscillator that will produce a sinusoidal waveform at a frequency of 25 kHz and use that signal to determine the value of resistance and capacitance for a model of tissue impedance based on measurements of your biceps. The oscillator is an op-amp Wein-bridge circuit that produces a sinusoid, as shown in Fig. 3. The sinusoidal output from the oscillator will drive a resistor in series with electrodes placed on both sides of your biceps. The resistor, whose value you will choose, and the tissue in your biceps will form a voltage divider. By measuring the magnitude and phase-shift of the voltage across the resistor relative to the 25 kHz sinusoid, you will be able to determine the value of R and C for a parallel RC model of the tissue. You will use an oscilloscope to make the necessary magnitude and phase-shift measurements.

2. DESIGN OSCILLATOR

2.1. Frequency-Domain Circuit

The Wien-bridge oscillator in Fig. 3 consists of an op-amp and two voltage dividers. One voltage divider consists of components on the left side: R_1, C_1, R_2, and C_2. The other voltage divider consists of components on the right side: R_3 and R_4. These two voltage dividers deliver a fraction of the op-amp output voltage, v_0, to the + and – inputs of the op-amp. Because the circuit has negative feedback, changes in v_0 act to make the voltages at the op-amp inputs equal. Because the circuit also has positive feedback, changes in v_0 also act to make the voltages at both op-amp inputs change in tandem, however. At first glance, the equilibrium value for v_0 would seem to be 0 V. This is true in all cases except the special case when the two voltage dividers output exactly the same voltage. In this case, the bridge is said to be balanced. Though it may be counterintuitive, a balanced bridge leads to oscillation, as we discuss next.

When the bridge is balanced, *any* value of v_0 causes the + and – input voltages of the op-amp to be equal. Because we are dealing with reactive components, the bridge is balanced for one particular frequency of sinusoid. If the bridge is balanced, this sinusoid may have any amplitude. This is equivalent to saying the circuit is an oscillator.

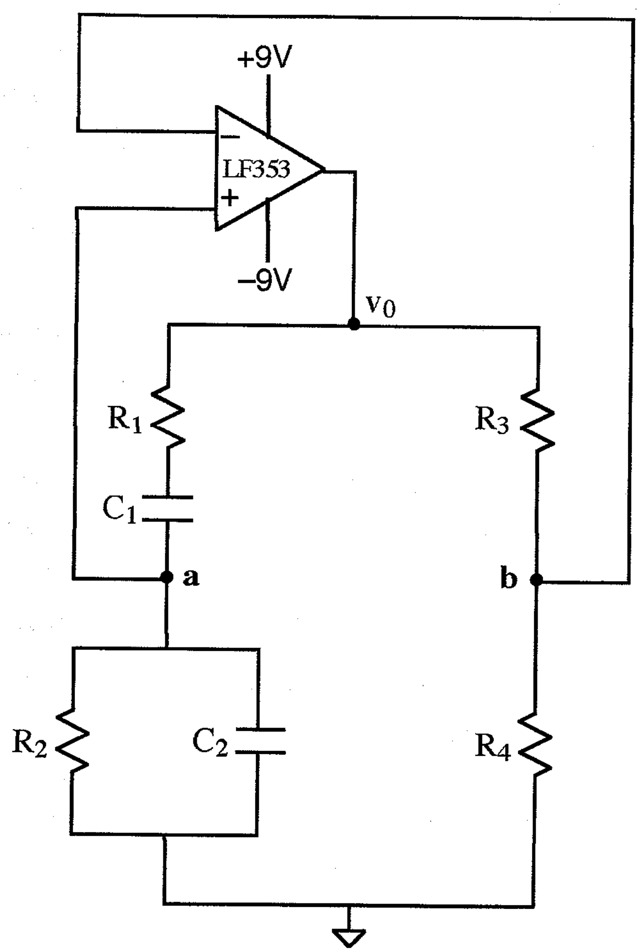


Fig. 3. Schematic diagram of an op-amp Wein-bridge oscillator.

The above discussion establishes that the circuit *may* oscillate. What ensures that the circuit oscillates is the presence of noise at the op-amp inputs. To establish this claim, we use frequency-domain techniques.

Transform the circuit of Fig. 3 to the frequency domain and read the following discussion before proceeding to the next section.

First, we note that, because of negative feedback, the op-amp output, $\mathbf{V_0}$, will move toward a value that makes the voltages at **a** and **b** equal. Using the idea of superposition, we may think of $\mathbf{V_0}$ as a superposition of signals of every possible frequency, with each such signal adjusted to make **a** and **b** equal. Given that the left and right side of the bridge are voltage dividers driven by the same voltage, $\mathbf{V_0}$, there are only two ways to make **a** and **b** equal:

condition in which no value of $\mathbf{V_0}$ will make the voltages at **a** and **b** equal. Consequently, the op-amp input voltages are unequal and $\mathbf{V_0}$ grows large. The balanced bridge thus gives rise to a large sinusoidal oscillation that is limited only by the power-supply voltages for the op-amp.

2.4. Oscillation Frequency

From the condition $Z_1/Z_2 = R_3/R_4$, derive an expression for the frequency of oscillation by solving for the value of ω that makes $Z_1/Z_2 = R_3/R_4$. Note that the quantity on the left is complex, whereas the quantity on the right is real. The equation is satisfied only if the real parts are equal and the imaginary parts are equal. This leads to two equations that must be solved. Show that one equation yields the value of ω, and the second equation is satisfied when $R_3/R_4 = R_1/R_2 + C_2/C_1$. (More advanced analysis shows that the condition for oscillation is $R_3/R_4 > R_1/R_2 + C_2/C_1$, but saturation of the op-amp occurs when R_3/R_4 is too high, producing clipping of the waveform.)

2.5. Component Values for Oscillation

Using $C_1 = C_2 = 250$ pF and the equations you derived above, choose component values for the circuit that make it oscillate at frequency $\omega_{ab} = 25$ kHz. Use practical component values that require less than the maximum 10 mA the op-amp can output. When designing for this constraint, consider the instantaneous current flowing out of the op-amp and find its maximum value during one cycle of the square wave.

3. CONSTRUCT AND TEST OSCILLATOR

3.1. Oscillation Frequency for Standard Component Values

Re-calculate the frequency of oscillation for the standard component values chosen for the circuit. That is, assume the components have exactly the standard value shown on their label.

3.2. Oscillation Frequency for Actual Component Values

Measure the values of the actual resistors and capacitors that you used in the circuit and re-calculate the frequency of oscillation for these component values.

3.3. Measured Oscillator Waveforms

Construct the oscillator circuit that you designed. Note that proper performance of the circuit requires that ratios of component values be very accurate. Match capacitor values by padding them with small capacitors added in parallel, if necessary, and use potentiometers instead of resistors to adjust resistor ratios where necessary. In particular, use a potentiometer for R_4, and adjust it so that the R_3/R_4 value makes $v_0(t)$ a good sine wave.

Record and plot the waveform on the oscilloscope and determine the frequency of the sinusoid.

3.4. Tabulated Values

Make a table showing the following values:

i. Desired oscillator frequency, (25 kHz).
ii. Predicted oscillator frequency for standard component values chosen for the circuit. That is, assume the components have exactly the standard value shown on their label.
iii. Predicted oscillator frequency for measured component values.
iv. Oscillator frequency measured on the oscilloscope.

4. ANALYZE TISSUE IMPEDANCE MODEL

4.1. Circuit for Measuring Tissue Impedance

As discussed in the Introduction, a simplified model of tissue impedance consists of a parallel R and C. Nominal values for R and C are $R_t = 2\ k\Omega$ and $C_c = 2.5$ nF. To determine the measured values of R_t and C_c, we use a voltage divider consisting of a known resistance in series with the tissue that is connected by electrodes. We measure the voltage, $\mathbf{V}_1$, across the total impedance and the voltage, $\mathbf{V}_2$, between the resistor and tissue to obtain two sinusoidal waveforms with different magnitudes and phase shifts. Using this information and some algebra, we can determine the values of R_t and C_c.

Using an external resistor in series with the oscillator output and the tissue model, design a voltage-divider experiment that allows you to determine the impedance of the tissue at 25 kHz. In other words, draw a schematic diagram showing the oscillator output, the external resistor, the tissue model, and connections for two oscilloscope probes with reference inputs. Note that the oscilloscope inputs have a common reference connection. Thus, you must choose a circuit configuration that uses two voltage measurements with a common reference. Furthermore, this reference must be the same as the reference of the oscillator circuit.

Show your measurement-circuit diagram to your TA for approval before proceeding.

4.2. Component Values for Tissue Impedance Model

Derive a symbolic equation relating tissue impedance, z_t, to the two phasor voltages, $\mathbf{V}_1$ and $\mathbf{V}_2$, that you will measure with your circuit. Extend your results to find equations for R_t and C_c in terms of $\mathbf{V}_1$ and $\mathbf{V}_2$. Note that complex quantities are equal if and only if the real parts are equal and the imaginary parts are equal.

4.3. Choosing Resistance for Impedance Measurement Circuit

Choose an external resistance value, R_1, that yields accurate R_t and C_c values when measured values of $\mathbf{V}_1$ and $\mathbf{V}_2$ include small errors. That is, choose a value of R_1 such that a small measurement error has minimal effect on the calculated values of R_t and C_c. Although an optimal value of R_1 value could be derived by sensitivity analysis, you may use a much more tractable alternative of finding a value of R_1 such that the ratio of the magnitudes of $\mathbf{V}_1$ and $\mathbf{V}_2$ is approximately two-to-one, depending on which is the larger signal. Use the nominal values of R_t and C_c from Subsection 4.1 for this calculation.

5. MEASURE TISSUE IMPEDANCE

5.1. Measurement of Tissue Impedance and Calculation of Component Values

Using an oscilloscope, your oscillator circuit (powered by 9V batteries), your external resistance, R_1, and two electrodes placed halfway up your biceps on the inside and outside edges as shown in Fig. 4 so a line connecting the electrodes runs through the muscle, measure $\mathbf{V}_1$ and $\mathbf{V}_2$ at 25 kHz. Then use your equations from 4.2 to calculate R_t and C_c. Also, measure the approximate distance, *d*, separating the electrodes and the surface area, *A*, of the electrodes.

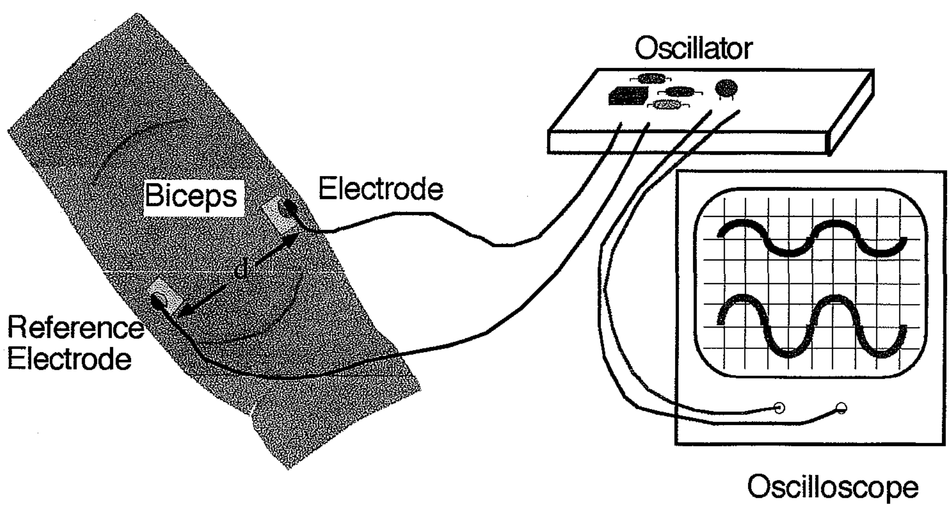


Fig. 4. Tissue measurement configuration.

5.2. Calculation of Conductivity, Relative Permeability, and Power Density

Use your calculated values of R_t and C_c along with *d* and *A* to find estimated values of the conductivity, σ, and relative permeability, ε_r, of your muscle for comparison with published values. Also calculate the power density, S, used in the experiment. The equations you will need come from basic physics and involve *only products or quotients* of physical quantities. By ignoring fringing fields and modeling the tissue between the electrodes as a tube, as shown in Fig. 5, derive equations for the following terms:

i. R_t as a function of d, A, and σ = tissue conductivity = 1/tissue resistivity in Ωm
ii. C_t as a function of d, A, and $\varepsilon = \varepsilon_0 \varepsilon_r$ where $\varepsilon_0 = 8.85$ pF/m and ε_r = unitless const
iii. Power density S (= total power in tissue divided by electrode area) in W/m^2 as a function of I = magnitude of electrode current, R_t, and A

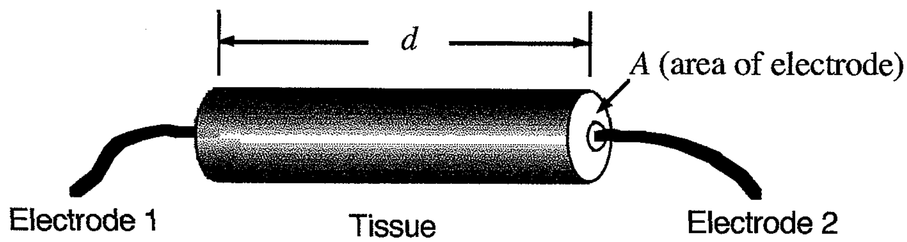


Fig. 5. Tissue modeled as a tube.

To determine whether R_t or C_t are proportional or inversely proportional to d or A, think of the tube of tissue being subdivided into thinner or shorter tubes connected in parallel or in series. Increasing A corresponds to adding components in parallel, while increasing d corresponds to adding components in series.

Rearrange your equations for R_t and C_t to solve for σ and ε_r. Use your measured value for $\mathbf{V}_1$ or $\mathbf{V}_2$, along with R_t and C_t, to calculate the magnitude of electrode current, i. Then calculate the values of σ, ε_r, and S.

5.3. Comparison of Measured Values with Published Values

Make a table comparing your values of σ, ε_r with values for muscle and fat found at

http://www.brooks.af.mil/AFRL/HED/hedr/reports/dielectric/home.html

in an appendix:

http://www.brooks.af.mil/AFRL/HED/hedr/reports/dielectric/Appendix.B/AppendixB1.html

5.4. Comparison of Power Density with FDA Limit

Compare your value of power density, S, with the FDA limit of 100 mW/cm^2 (for higher frequency) published on the web at

http://www.fcc.gov/Bureaus/Engineering_Technology/Documents/bulletins/oet65/oet65.pdf (see p. 67, Table I(B) value for 0.3 MHz).

6. WRITE FORMAL REPORT

Write a formal report describing your work on this project. See instructions in "Course Procedures" about how to write the report. (Also, look for detailed point breakdowns for Lab 3 grading on the course web site.) Include at least the following in your report:

i. An abstract. The abstract is a one paragraph succinct summary of the entire results. It should describe the key result of the experiments performed.

ii. A short introduction. You may attach this handout to the report in the appendix and refer to it so that you don't have to copy the information in it. Your introduction, however, must introduce your report and will be unique to your report. The introduction gives the motivation for the experiments performed and describes the organization of the report.

iii. A careful description of the work that you did in Sections 2 through 5, above.

   a. Discuss and give appropriate quantitative results for each of the numbered subsections in Sections 2 through 5. Every subsection corresponds to a specific task with a specific quantitative result that must be described in your report. To facilitate grading, number the subsections of your report with the same numbers used in this handout.

   b. Give clear derivations of mathematical expressions, including explanations in words for every equation in every derivation. Include consistency checks of final results whenever possible.

   c. Explain how you chose the values of circuit components and include a schematic diagram showing component values for the final circuit.

   d. Explain all measurements carefully and include data appropriately in clearly labeled tables and graphs in the body of the report.

   e. Include listings of all your Matlab® programs in an appendix, and explain how the code works in comments.

   f. Show plots of your oscillator output and voltage waveforms for the tissue impedance measurement.

iv. A succinct conclusion. The conclusion must list the most salient quantitative results of this laboratory project. As a guide to what the conclusion should say, consider what information would be most useful to a student about to start the lab.

30		***Communication***
12		Student's work Reproducible from notebook
4		Written in Ink
4		Student Signed every page
4		Student Dated every page
6		TA Signature for every lab session (-3 each session missed)
26	**2.**	***Design Oscillator***
5		2.1. Frequency-Domain Circuit
5		2.2. Balanced Bridge
5		2.3. Oscillation
6		2.4. Oscillation Frequency
5		2.5. Component Values for Oscillation
18	**3.**	***Construct and Test Oscillator***
4		3.1 Oscillation Frequency for Standard Component Values
5		3.2 Oscillation Frequency for Actual Component Values
5		3.3. Measured Oscillator Waveforms
4		3.4. Tabulated Values
11	**4.**	***Analyze Tissue Impedance Model***
3		4.1. Circuit for Measuring Tissue Impedance
5		4.2 Component Values for Tissue Impedance Model
3		4.3 Choosing Resistance for Impedance Measurement Circuit
15	**5.**	***Measure Tissue Impedance***
5		5.1. Measurement of Tissue Impedance and Calculation of Component Values
6		5.2. Calculation of Conductivity, Relative Permeability, and Power Density
2		5.3. Comparison of Measured Values with Published Values
2		5.4. Comparison of Power Density with FDA Limit

LABORATORY PROJECT NO. 3
Report Grading

THE UNIVERSITY OF UTAH

25		***Communication***
5		Clarity of style (ease of reading, and etc.)
4		Organization (ease of locating figures/code/etc)
4		English (grammar, punctuation, and etc.)
4		Section numbers and headings (use section numbers shown below)
4		Equations explained (at least one sentence between equations)
3		Figure titles and numbers
5		Matlab listings and comments (put in appendices)
5		***Abstract*** (succinct summary of numerical results)
5	**1.**	***Introduction*** (motivation for lab, overview of report organization)
21	**2.**	***Design Oscillator***
5		2.1. Frequency-Domain Circuit
4		2.2. Balanced Bridge
4		2.3. Oscillation
4		2.5. Oscillation Frequency
4		2.6. Component Values for Oscillation
14	**3.**	***Construct and Test Oscillator***
3		3.1 Oscillation Frequency for Standard Component Values
3		3.2 Oscillation Frequency for Actual Component Values
4		3.3. Measured Oscillator Waveform
4		3.4. Tabulated Values
10	**4.**	***Analyze Tissue Impedance Model***
3		4.1. Circuit for Measuring Tissue Impedance
4		4.2 Component Values for Tissue Impedance Model
3		4.3 Choosing Resistance for Impedance Measurement Circuit
15	**5.**	***Measure Tissue Impedance***
5		5.1. Measurement of Tissue Impedance and Calculation of Component Values
6		5.2. Calculation of Conductivity, Relative Permeability, and Power Density
2		5.3. Comparison of Measured Values with Published Values
2		5.4. Comparison of Power Density with FDA Limit
5	**6.**	***Conclusion*** (summary of key results, including numerical values)