Electroencephalograph (EEG)

Final Project Part 1: Design and Simulation

ELECTRICAL ENGINEERING 43/100

INTRODUCTION TO MICROELECTRONIC CIRCUITS

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Final Project Overview and Objectives

For your final project, we will be building an electroencephalogram (EEG) on the breadboard. We will be working on designing (1st week) and building (2nd) EEG circuit for the rest of the semester.

In this project we will design, simulate, and build EEG circuits. Since this is your final project, obviously we will be using a significant portion of what you learned in previous labs about various circuit components and analysis techniques. Therefore, if you’re a little rusty on some of the things we did in previous labs; it would be a good idea to brush up on what you do not feel comfortable with because you essentially built most of the modules already in previous labs.

As with all other labs, we will start with design considerations and parameters, and simulate our circuit in Multisim. After the design process, we will construct our design in on the breadboard! In the real world, engineers usually transfer their designs to Printed Circuit Board (PCB), like the one you soldered at the first lab, after testing and deliver the products. However, we will not be designing a PCB for this project.

This may seem a little overwhelming at first, but relax; we will try to make this as painless as possible.

Project Parameters

Let’s consider our project specifications. Below are the project specifications that your design for your EEG must meet along with any metrics of evaluation. Each module of the project is covered in detail in the next section.

Design Specifications

- You must use an instrumentation amplifier built from discrete components with appropriate gain
- The instrumentation amplifier must have adjustable gain
- Any other amplifier stage must also have adjustable gain
- You must use a +/- 5 V regulators to obtain +/- 5 V from the 9 V batteries.
- You must have coupling and decoupling capacitors in appropriate parts of your circuit
- You must have voltage followers where necessary

Part Specifications

The following parts are available for your design. You will be provided a kit with these parts at the beginning of the prototyping phase provided that you have a schematic ready to build. You will not receive the kit if you do not complete the schematic beforehand. Kits will be distributed one per group. Since, we have already given you breadboard in the previous lab, the kit will not contain breadboard. It is your responsibility to figure out how these components work and look at the datasheets.

- 4 x TLC277CP Dual Operational Amplifier
- 1 x LM7805 +5V Regulator, 1x LM7905 -5 V regulator
- 1 x 10 kΩ potentiometer (for instrumentation amplifier gain control)
- 4 x 50k 1% tolerance resistors (for instrumentation amplifier input stage and gain stage)
- 2 x 500k 1% tolerance resistors (for instrumentation amplifier input stage and gain stage)
- 1 x 1M resistor (for filtering)
- 1 x 100k resistor (for filtering)
- 1 x 5kΩ potentiometer (for gain control in active low pass filter)
- 2 x 10 ohm resistors (for notch filter)
- 2 x 20kΩ resistor (for notch filter)
- 2 x 247kΩ resistor (for notch filter)
- 1 x 1 uF capacitor (for filtering)
- 1 x 0.01 uF capacitor (for filtering)
- 2 x 0.22 uF capacitors (for filtering)
- 2 x 10 uF capacitors (for filtering)
- Header pins for test pad connections
- 4 x 8 pin DIP sockets for each of your 8 pin chips
- Any other components you would like to add

Performance Specifications

- All excess high frequency noise must be adequately attenuated
- You should have a spike at 10 Hz on the frequency spectrum and a strong DC component
- **You will NOT under any circumstances test this device on yourself (we’re not going to supply you electrodes anyway)**
- The circuit should perform completely off two 9V batteries

Due Dates for this Project

- The deadlines for this project are as follows:
  - Schematic Design and Simulation: **Beginning of lab, the week of April 15th. (You must check your design with a GSI)**
  - Final Breadboard, Demonstration, and Lab Write Up: **Due Week of May 6**.
- You should start on this project early, otherwise you may not finish the project on time.

Design Phase

Before we begin building EEG circuit, we want to design the circuit and do a design analysis. Our EEG will either take a brainwave signal or a test signal. Because the signal is so weak (10⁻⁶ V), we’re going to have to amplify the signal by several orders of magnitude in order to apply appropriate signal processing. Therefore, we will first send our signal through an instrumentation amplifier. However, we might not be able to get adequate gain with just one amplification stage. In addition, having several adjustable amplification stages will allow us to have higher resolution in amplification.

At this point, our EEG should have amplified our signal enough to apply filters and various signal processing techniques. As mentioned before, the main signal components of the brainwave signal that we want to capture is around 10Hz. In addition, we also have to eliminate any signal noise that we may have picked up. Since noise is usually a high frequency component, and we are looking for a low frequency component, we will apply a low pass filter to extract the brainwave signal. We should then be able to take the output signal and display it on an oscilloscope.
The Electrode

We will be providing you the electrodes to test with after you finish the board. Every group will NOT receive an electrode; we will have a set that we will use for testing and you will return these after testing. ABSOLUTELY at any time, do not test the EEG on yourself.

Electrodes

To ensure that our unfortunate test subjects are protected from electrical shock, our electrodes will be equipped with protection circuitry so that testing will be safe. For those of you who are interested, the schematic of the protection circuit is given below. Basically what it will do is ensure that when we test your circuit on us, we don’t get zapped.

Luckily we have already built these electrodes for you and eliminated most of the issues associated with these problems. Again, we will not be providing electrodes for you to take home since they are expensive and we don’t feel like dealing with the paperwork to make it legal.¹

¹ An appropriate lawyer joke would go here
The Instrumentation Amplifier Stage

Since the signal strength we are processing is on the order of $10^{-6}$ V, we have to apply an incredibly high gain in order to bring it into a range that we can process the signal. Recall in lab 4, we used an instrumentation amplifier which can be configured to have high gain.

The instrumentation amplifier that you encountered is lab 4 is shown below:

In the space provided below, prove that the gain of the instrumentation amplifier is given by:
$$v_0 = \left( \frac{R_4}{R_5} \right) \left( \frac{R_1 + R_2 + R_3}{R_2} \right) (v_2 - v_1)$$

$$v_0 = \left( \frac{R_4}{R_5} \right) \left( \frac{R_1 + R_2 + R_3}{R_2} \right) (v_2 - v_1)$$

In addition, choose reasonable values such that the instrumentation amplifier has a gain of ~1000 using a 10kΩ potentiometer. (Since specific parts are given for this project, you should check the part list to see what components you can use). Provide all relevant calculations that prove your values satisfy the specifications. Show the Multisim simulations and measure the gain in the simulation. (Set $V_1$ to ground, and $V_2$ a ~10 Hz AC signal with the voltage amplitude in the order of $10^{-5}$ $V$. The supply voltages of the op-amps are ±5 $V$.)

**Pre-Lab Score:__/15**

**DC Block**

Following the first stage, we will need to put in a DC block to block DC signals. Remember, the signal that we are processing is being amplified from a microvolt signal strength and the brain wave signal component that we want to read is around 10 $Hz$. Thus, to clean things up a little bit, we can apply a high pass filter with a very low cutoff frequency which can easily be done by a resistor and capacitor shown below.
High Pass Filter DC Block

For our circuit we will be using the DC block with a cut off frequency of \( \sim 16 \text{ Hz} \). For this we will be using a \( 1 \mu F \) capacitor and \( 1 \text{ M\Omega} \) resistor. Recall, the cutoff frequency in rad/s for this filter is \( \omega_c = \frac{1}{RC} \).

The Non-Inverting Active Low Pass Filter

So at this point, we've done quite a bit of amplification and signal fluffing, but haven't really amplified the signal enough nor filtered out all of its undesired components. As discussed earlier, the frequency that we want to see from our EEG lies around the \( \sim 10 \text{ Hz} \) range so we have to extract that from our amplified signal. So let's stop piddling around and do that.

First, we're going to throw a low pass filter at our signal. For our application, we're going to use a non-inverting active low pass filter which is shown below:

We're going to draw a bode plot for the active low pass filter (it may be helpful when we analyze the next filter). In the space provided below, show that the gain of the non-inverting active low pass filter and cutoff frequency is given by the following:
\[ \omega_c = \frac{1}{R_5 C_4} \]

\( Z_2 \) is the impedance of \( C_4 \) and \( R_5 \) in parallel. Before you begin a mathematical derivation of the gain, think \( c \to \text{infinity} \)? This should give you an idea of why the circuit is a low-pass filter. Plugging in values for different angular frequencies and computing the change in gain will also help you understand the circuit more. Remember that the cutoff frequency above is in rad/sec, not Hertz!

In addition, draw the Bode plot and label any relevant points in terms of the given variables. Finally, choose values \( c \) is 1000 rad/sec and the DC gain is 100. Show the MultiSim simulation to confirm your results. The supply voltage of the op-amp is \( \pm 5 \) \( V \).

Pre-Lab Score:___/15

The Notch Filter

So the low pass filtering was nice, but it doesn’t really give us exactly what we want. Remember that EEG signals are on the order of \( \sim 10^{-6} \) \( V \) which means that the amount of noise we have to deal with is fairly annoying. Our active low pass filter did attenuate many of the higher frequencies but it is limited to a \( -20 \text{dB/decade} \) dropoff.

In order to fine tune our signal, we are going to apply a cascade of notch filters to eliminate some \( 60\text{Hz} \) noise. The \( 60\text{Hz} \) noise is due to the electrical power lines. Once again, since our circuit is dealing with such low voltage signal, we need to consider this electrical interference.
For those of you who don’t know what a notch filter is, don’t panic. Basically a notch filter passes all frequencies except for a narrow range and is called a notch filter because its frequency response looks like it has a “notch” in it. The plot below is the theoretical plot of the magnitude response of our notch filter from Mathematica.

![Notch filter frequency response](image1.png)

As you can see from the magnitude plot above, a notch filter is ideal for killing any particular undesired frequency such as the 60 Hz component we wish to eliminate. The same notch filter magnitude plot is shown below in MultiSim.

![Notch filter frequency response in MultiSim](image2.png)

Notice in MultiSim we have two magnitude plots. The reason is that one of the magnitude plots belongs to the notch filter realization shown below.

![Notch filter circuit](image3.png)

Note we are using the impractical value of 26.5 H for our inductor! So, how did we get a practical circuit close to our theoretical performance? The answer is the gyrator, a circuit that “inverts” impedances. Consider the circuit shown below (from Wikipedia).
First, prove below that the op-amp gyrator circuit above has

\[ Z_{in} = R_L + j\omega R_L C \approx R_L + j\omega R_L C \]

Here, since \( R_L \) is small, we can ignore the term of \( j\omega R_L C \) in the denominator. Hint: you should recognize negative feedback configuration for amplifier and apply test voltage source (\( V_{test} \)) at the input and then find the total current drawing out from test source. Total impedance \( Z_{in} \) can be found by \( \frac{V_{test}}{i_1 + i_2} \).

**Pre-Lab Score: ___/15**
In our usage of the gyrator for our notch filter, we will use the following variation:

Derive the transfer function of the circuit above. Use $RL1 = 10 \text{ ohms}$, $Cg1 = 10 \text{ uF}$ and remember that the inductor you are simulating is $26.5 \text{ H} \ (\sim RL1 \cdot RCg1)$. Choose $R2 = 20k$ and $f_c \approx 60\text{Hz} \ (\text{notch frequency})$, this should help you solve for $C2$ and thus you should be able to draw a magnitude Bode plot (no phase required). Show YOUR OWN MultiSim simulation results to confirm your Bode. Make sure they agree with our previous STANDARD simulation results from MultiSim. The supply voltage of op-amp is $\pm 5V$.

Pre-Lab Score:___/20
Note that in our application, we are going to cascade two notch filters (we’re going to kill the 60 Hz frequency twice for good measure). The implementation for this portion of the circuit is shown below.

The Bode plot for the cascaded notch filter is shown in the following.
Powering Your Circuit

To power your circuit, we will be using two 9V batteries to provide ±5\(V\) power supplies to your circuit. In order to do this, we will be using ±5\(V\) regulators. The regulators in question are the LM7805 and LM7905 regulators. In the space below, look at the datasheet for these components and draw the circuit diagrams showing how to connect them. Clearly indicate where the 9V battery goes and where the ±5\(V\) output is.

Pre-Lab Score: ___/5

Output Signal and Testing

Once we have finally finished processing the signal in the lab, we are going to send it to an oscilloscope so that we can actually see the EEG signal. To test your signal, you can either sweep frequency on DC analysis or put a bode plotter in the Multisim. On the real circuit, you should use the function generator to generate different frequency signal and look at the output on the oscilloscope to see if the gain matches with simulation value. Everyone’s signal will look different but generally you will end up with a strong DC component and weaker spike around 10\(Hz\).

What you need to do...

Your task is to complete the rest of the EEG design, put everything together, and simulate it in Multisim. We recommend that you draw a rough draft on a spare sheet of paper so that you have a good idea of where you are going when you start to place components in Multisim.
Make sure to attach a copy of your working schematic and simulation results to the lab report. Show that your simulation results meet the design specifications described above. It would be great if you simulate your circuit by modules and show (submit) to the GSIs. This part of the lab is due the first lab session for the final project.

In addition, you will need to get your schematic checked off by your GSI in order to get your parts kit.

You will not have to consider the following when completing the design of your circuit since we have already accounted for them in the modules presented above:

- Bypass Capacitors – to prevent voltage sags and mediate the effect of abrupt current draw fluctuations
- Buffers – to match input and output impedance between different modules
- Output Resistors – to match output impedance

We also recommend that you build and test your circuit in modules. This will increase the chances that you will be able to catch errors and debug your design.

Also use clean wiring in your schematic because it makes it easier for us and for you to trace your circuit. We will refuse to help groups that do not wire their circuits cleanly. This is a fairly large circuit and if you don’t wire things neatly, you will be hopelessly confused and proceed to throwing fragile objects.

Tips on Simulation and Testing...

- To test your circuit in the simulator you will have to generate an oscillating signal using an AC voltage source or something equivalent. Make sure that this source is set to a microvolt level signal ranging from around a few $\mu V$ to 100 $\mu V$. Unfortunately since our lab instruments won’t be able to generate such low voltage signal we will have to use something else when we actually build and test our circuit (we’ll worry about this later though...).
- When you do put your circuit in the simulator, make sure that you build it modularly and that each part of the circuit is clearly identified. This is to help you and to help us quickly debug your schematic should there be any obvious problems. You may want to label each module on the circuit with a short description.
- When you are simulating your entire EEG circuit, you may need to set the DC Convergence Limit to 2000 and Transient Convergence Limit to 1000 if you end up getting convergence errors.
- Make liberal use of the virtual multimeters, probes, scopes, and Bode Plot analyzers that Multisim provides you. These are the primary ways you will be able to tell whether your simulation is actually working or not. Make sure to probe key points in your circuit like between critical modules and check to see if the outputs you are reading match with what you expect.

Since there are a lot of pieces to the prelab, included below is a list of everything you should include with your prelab:
1. Analysis and Multisim of Instrumentation Amplifier
2. Multisim simulation of DC Block (optional, but recommended)
3. Analysis and Multisim of Non-inverting Low Pass Filter (LPF)
4. Analysis and Multisim simulation of Notch Filter
   a. Magnitude bode plot of single gyrator
   b. Magnitude bode plot of cascaded gyrators
5. Multisim simulation of power regulators (optional, but recommended)
6. Multisim simulation of entire circuit with designed building blocks
   a. Include instrumentation amplifier, DC block, non-inverting LPF, cascaded notch filters, power regulators

Note: Although the lab report doesn’t require individual plots for the DC block and power regulators, it’s always a good idea to test individual blocks before simulation them in the complete circuit.
Building EEG

Now that you have your schematic ready to go, it is now time for you to actually build your circuit.

Some of you may be tempted to throw everything on the breadboard at once and test functionality at the end. This is not a methodical approach to a project of this scale. If your circuit doesn’t work, the error could be anywhere in your circuit. Furthermore, you may have made multiple errors which could be anywhere in your circuit. Hopefully, you have learned quite a lot of debugging skills from previous labs as GSIs will not be always available to you.

Therefore, we recommend that you build your circuit in modules. This will enable you to test the functionality of each module and minimize the time you spend looking for bugs before moving on.

The order in which you build the circuit is entirely up to you. The key part of the process is testing functionality and debugging, since one mistake usually cripples the entire circuit.

In the following sections, we will provide you with some basic ways to test if your circuit module is working properly.

Before you start building up your circuit, we’d like to offer some basic tips:

- **Set current limits** on your power supplies. $P = IV$ means if you make a mistake and run too much current through your operational amplifier, timer, hand, etc. you will destroy it. The current limit is a failsafe mechanism that will limit the maximum current and eliminates the risk of breaking your components. **ASK YOUR GSI IF YOU DON’T KNOW HOW TO SET IT.**

- When you get stuck, **don’t disassemble your circuit until you’ve verified it’s a design problem.** We know sometimes it’s tempting to take apart your circuit and try again without taking a closer look at what might be wrong. It might be something simple such as a loose wire or bad power supply. Make sure to check these before deciding to take apart your circuit.

- **Use clean wiring.** This enables other people such as your GSI to help you debug your circuit. If your wiring is a mess, it’s harder to trace your circuit and takes more time for us to help you out. Your wires should also not be more than an inch or two above the board. **We will refuse to help groups that do not use clean wiring.**

- **The multimeter and oscilloscope are your friends.** If your circuit is not working, the first thing you should do is measure, measure, and measure, to find out where and what the problem is. Trace the entire signal path starting from the source and try to identify where the error is starting.

Testing Tips

As mentioned before, you should be building you circuit in modules and effectively testing each module before you continue your prototyping. Testing each module for functionality is critical as it will help you isolate bugs to a smaller portion of your circuit and fix them. Below are a few tips on how to test each of your circuit modules in isolation.
Note, however, that when you finally go to test the entire circuit, you will want to use 9V batteries since bench supplies have a strong 60 Hz noise component. We recommend that once you get to that point in the testing, that you use the voltage regulators and batteries to produce the supplies.

The Instrumentation Amplifier Stage

- Recall from lab 4, we used the instrumentation amplifier to detect extremely small fluctuations in voltage difference. Similarly, to test that your instrumentation amplifier has adequate gain, you will probably want to supply it with some known input voltage from your power supply and probe the output to see if you are in fact getting the desired gain. Be careful of saturation when making this measurement.

- The resistors supplied for the instrumentation amplifier have very small tolerances (1%). However, for best results, try to find resistors that should be the same in this stage, try to get the resistances as close together as possible. For example, if there are two $10k\Omega$ resistors in your stage, use the multimeter to try and find two resistors as close to each other and $10k\Omega$ as possible.

- When you fire up your instrumentation amplifier, if things are getting hot, make sure that you connected power supplies to your operational amplifiers correctly. If your resistors are getting hot, you probably want to use a higher value resistor.

- Make sure to supply your circuit with ±5 volts since that is what we’ll be using in the actual circuit.

- If you’re not getting a signal at all, you probably want to double check that everything is connected correctly. If you’re wiring is bad, fix it before pulling over a TA.

- Test your circuit and fill in the table below. **(10 points)** The gain ideally shouldn’t change with frequency.

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<thead>
<tr>
<th>Frequency</th>
<th>Peak-to-peak value of input</th>
<th>Peak-to-peak value of output</th>
<th>Gain/Attenuation Factor</th>
<th>Gain/Attenuation in dB</th>
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The Active Low Pass Filter Stage

- We recommend using a function generator as your input to this module and testing the output with an oscilloscope. This way you can sweep a range of frequencies on the function generator and see if your filter kills and passes the correct ranges of frequencies.

- Use the peak-to-peak measurement option on the oscilloscope to make sure you are obtaining the correct amplification or attenuation at the correct frequencies.

- Make sure you send in the test signal at the correct node in the circuit and appropriate nodes are grounded.

- Again we recommend using a function generator and running a sweep of the frequencies to ensure the frequency response is correct and using the peak-to-peak measurement option on the scope to check amplification and gain.

- You can also test this module for gain using a constant voltage signal and measuring the output with a DMM since a DC voltage corresponds to $\omega = 0$. Since this is a low pass filter stage, make sure you are getting maximum amplification at $\omega = 0$.

- Test your circuit and fill in the table below. (10 points)

**Measured cut-off frequency $fc =$**

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<th>Frequency</th>
<th>Peak-to-peak value of input</th>
<th>Peak-to-peak value of output</th>
<th>Gain/Attenuation Factor</th>
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Notch Filter Stage

- Again we recommend using a function generator and running a sweep of the frequencies to ensure the frequency response is correct and using the peak-to-peak measurement option on the scope to check amplification and gain.

- You can also test this module for gain using a constant voltage signal and measuring the output with a DMM since a DC voltage corresponds to $\omega = 0$.

- For the notch filter, we really only expect frequencies in a very narrow region to be killed, so make sure that you don’t “miss” that frequency band in your sweep.

- Test your circuit and fill in the table below. (10 points)

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<th>Frequency</th>
<th>Peak-to-peak value of input</th>
<th>Peak-to-peak value of output</th>
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The Final Test Circuit

Once you have assembled all of the modules, and tested them, you are ready to put the whole thing together and finish the final test. Unfortunately we can’t just use the function generator to shove the microvolt level signals we need to simulate. So how can we test our circuit? (Hint: Voltage divider)

Final Testing
Once you have confirmed your EEG circuit is working properly, you should gather some data. Make sure to have your oscillator circuit hooked up to your EEG and the scope displaying the output.

Set the frequency of the input AC signal to be 10Hz, and amplitude in the order of $10^{-6} \sim 10^{-5}$ V. Adjust your potentiometers to get desire gain.

Based on your measurement, fill in the following table for the whole EEG circuit. (10 points)

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<th>Peak-to-peak value of input</th>
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Your GSI Signs Here (40 points) 

Can you detect brain signal? (20 points)