Lab 3 Write-Up

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November 7, 2018

1 Introduction

The purpose of this lab is to design and construct a circuit that creates a voltmeter using a galvanometer. A galvanometer is an indicator that moves a needle along a scale according the the amount of current flowing through the coil of wire attached to it. The needle is at the center position of the indicator when there is zero current running through the galvanometer. When current flows through the coil of wire, the needle will be deflected from the center. Further deflection of the needle will be seen with more current flowing through the wire. The galvanometer is characterized by its full scale deflection (the maximum deflection of the needle from the center). The one we used for this circuit will be maximally deflected when 50μA of current runs through the coil.

The galvanometer and the voltmeter circuit come with several specifications. The specifications for the voltmeter circuit include:

- The full scale input voltage is 1V
- The input resistance is $\geq$1MΩ
- The reading for an input that is grounded or open should be 0

The specifications for the galvanometer include:

- 1μA per tick on the face of the galvanometer
- At full deflection of the needle, the current is 50μA
- The device has 2.5% accuracy
- No more than 60μA of current should be allowed through the galvanometer

The overall goal of this lab is to design a voltmeter circuit that successfully measures current using the galvanometer, while meeting all of the specifications listed above.

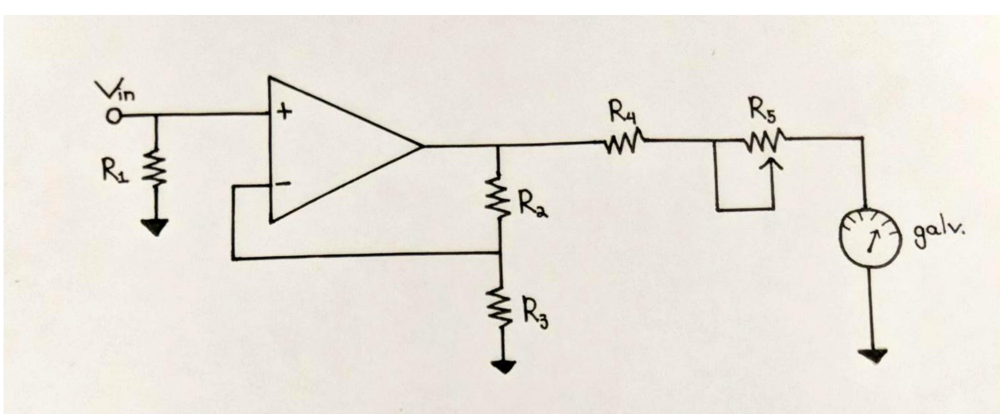

Figure 1: Design 1 Skeleton Circuit

2 Voltmeter Design 1

This first circuit design uses an op-amp to create a voltage amplifier for the galvanometer. The first step of designing a circuit is to draw out the skeleton circuit, which is a diagram of what the circuit will look like, without giving specific values for each device involved in the circuit. The skeleton circuit is shown in Figure 1.

2.1 Choosing the Op-Amp

The next step in designing this circuit is to choose the model of the op-amp we are going to use. After consulting the properties of the different op-amps available, we decided that the ICL7650S was the model best suited to meet our specifications. Since the galvanometer has a 2.5% accuracy, we want to keep the offset voltage of the op-amp below 25mV (since 2.5% of 1V is 25mV) to account for this potential error. The ICL7650S op-amp has the lowest typical offset voltage and maximum offset voltage, so this model is the one that is most likely to keep the offset under 25mV after it's multiplied by the gain. Additionally, the ICL7650S is powered by 5V, which is lower than the other op-amps. Since the op-amp is powered by 5V, the output voltage of this device will not go over 5V. Keeping the maximum output voltage low can make it easier for us to prevent more than 60μA of current from going through the galvanometer, as required by the specifications.

2.2 Choosing the Resistors

The next step before finalizing the circuit design is to choose the values of all of the resistors.

We began by choosing the value for R_1, which is the grounded resistor at the positive terminal of the op-amp. One of the specifications dictates that the input resistance should be greater than or equal to $1M\Omega$, and since this is the resister at the input terminal, it was chosen to be $1M\Omega$ to meet this specification.

R_4 and R_5 are chosen in order to meet the specification that no more than 60μA of current should go through the galvanometer. The steps to find these resistors requires some math:

The first step is to notice that R_4, R_5, and the galvanometer are all in series, so to simplify things we can define the sum of all of these resistances to be R_{fixed}. A diagram of this is shown in Figure 2.

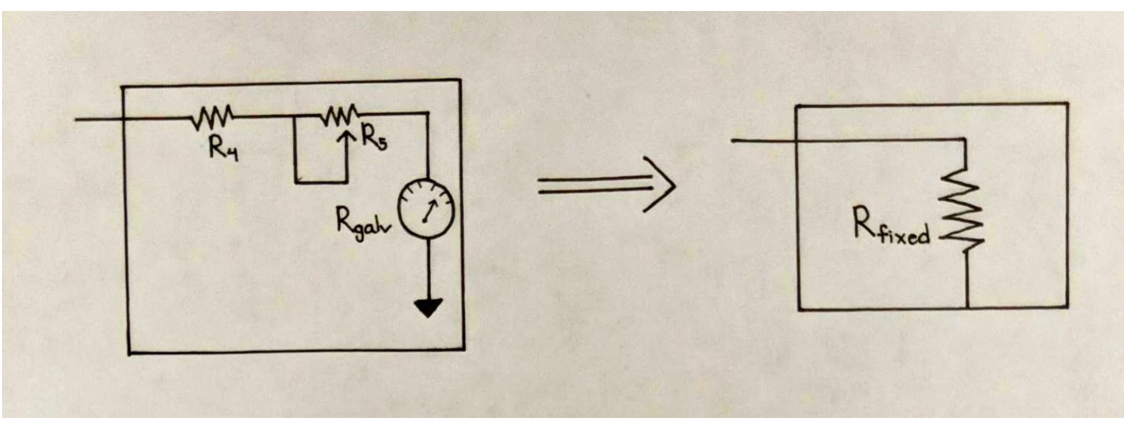

Figure 2: Redefining $R_4 + R_5 + R_{galv}$ as R_{fixed}

The next step is to find the value of R_{fixed}:

- Start with the equation $V = IR$
- The value of V is $5V$, since the maximum output voltage of the op-amp is $5V$.

- The value of I is set to be 55μA. Solving for 55μA rather than 60μA (the maximum current allowed in the specifications) gives more insurance that the current going through the galvanometer will not go above 60μA. Since errors could be present in the circuit, it's best to instead solve for a value that splits the difference between 50μA and 60μA.
- Solve for R_{fixed} using this equation and the chosen values:

$$5V = (R_{fixed})(55\mu A)$$

$$R_{fixed} = \frac{5V}{55\mu A}$$

$$R_{fixed} = 91k\Omega$$

Now that we know R_{fixed}, we can find the values of R_4 and R_5:

- We already know that the resistance of the galvanometer is $1k\Omega$.
- From here we can find the sum of R_4 and R_5:

$$R_4 + R_5 + R_{galv} = 91k\Omega$$
$$91k\Omega - 1k\Omega = 90k\Omega$$
$$R_4 + R_5 = 90k\Omega$$

- R_5 is indicated as being a potentiometer in the skeleton circuit. Since the sum of the pot resistance and R_4 is pretty high, we can reason that it's a good idea to use a higher value for the pot. With this in mind, we chose a potentiometer that has a maximum resistance of $25k\Omega$.
- From here we can solve for R_4:
  - Half of the full resistance of the pot is $12k\Omega$.
  - If we subtract $12k\Omega$ from $90k\Omega$ (the total resistance of R_4 and R_5), we get $78k\Omega$. This will be the value of R_4.

Finally, we can find the values for R_2 and R_3:

- First, we want to find the value of $V_{out,fullscale}$. This is the value of the maximum output voltage of the op-amp:
  - Use the equation $V = IR$
  - The voltage at $V_{out,fullscale}$ is going to be equivalent to the voltage drop between the output of the op-amp and ground. Since we know the value of R for the path to ground going through R_4, R_5, and R_{galv}, as well as the desired value for current going through this path, we can use this to solve for $V_{out,fullscale}$:

$$V_{out,fullscale} = \frac{R_{fixed}}{50\mu A}$$

$$V_{out,fullscale} = (\frac{5V}{55\mu A})(50\mu A)$$

$$V_{out,fullscale} = 4.55V$$

- Use $V_{out,fullscale}$ to find the gain:
  - To find the gain, we can just use the simple equation

$$V_{out} = (Gain)(V_{in})$$

  and solve for V_{out}. (In this case, V_{out} is the value that we found for $V_{out,fullscale}$

– We know that the input voltage is $1V$, and the output voltage is $4.55V$.

$$Gain = \frac{V_{out}}{V_{in}}$$
$$Gain = 4.55$$

- Use the value for gain to find R_2 and R_3:
  – Start with the equation for gain:

$$Gain = 1 + \frac{R_2}{R_3}$$

  – Using the value that we found for gain, we found the desired ratio for R_2 and R_3:

$$4.55 = 1 + \frac{R_2}{R_3}$$
$$\frac{R_2}{R_3} = 3.55$$

  – Now that we know the ratio of R_2 and R_3 is 3.55, the next step is to find two resistors available in the lab whose ratio will allow us to come as close to this value as possible.
  – The resistors we found that gave us a ratio closest to the desired value were a $5.6k\Omega$ resistor for R_2, and a $1.5k\Omega$ resistor for R_3. These resistors gave us a ratio of 3.73, and a gain of 4.73.

To summarize, the values we found for the resistors in this circuit are:

- R_1 was chosen to be $1M\Omega$
- R_2 was found to be $5.6k\Omega$
- R_3 was found to be $1.5k\Omega$
- R_4 was found to be $78k\Omega$
- R_5 is a $25k\Omega$ potentiometer

2.3 Building the Circuit

Now that we know our op-amp model and the values of all of the resistors, we are ready to produce a final design for the circuit that includes all of the parameters we just came up with. The finalized circuit design is shown in Figure 3.

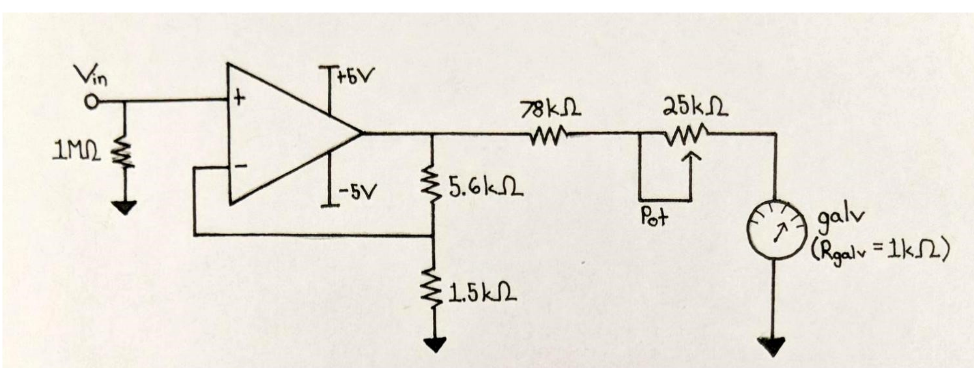

Figure 3: Final Design for Voltmeter Circuit Design 1

With the final design set, we are ready to begin building the circuit.

- We began by installing an ICL7650S op-amp into the breadboard.
  - After installing the op-amp, we hooked up the $5V$ power supply to it by attaching the $+5V$ supply to pin 7, and the $-5V$ supply to pin 4.
- The input voltage was connected to the positive terminal (or pin 3) of the op-amp.
- Since the design calls for a $1M\Omega$ input resistance, the $1M\Omega$ resistor was placed going from the postive terminal of the op-amp to ground.
- The $5.6k\Omega$ resistor connects from the output (pin 6) of the op-amp to the $1.5k\Omega$ resistor is connected to ground.
  - A feedback loop is created by connecting a wire to the negative terminal (pin 2) of the op-amp to the spot in between these two resistors.
- Before building the rest of the circuit, we tested out what we have built so far in order to ensure that we are getting the expected output voltage:

$$V_{in} = 1V, Gain = 4.73$$
$$V_{out} = (V_{in})(Gain) = (1V)(4.73) = 4.73V$$

  - As seen above, our expeced output voltage is $4.73V$.
  - The measured output voltage was $4.7V$, which is slightly lower than the expected output, but since it's only off by a negligible amount we can let it slide.
- To build the rest of the circuit, we attached $78k\Omega$ of resistance in place for R_4, and installing a $25k\Omega$ potentiometer for R_5.
  - We actually ended up using one $68k\Omega$ resistor and one $10k\Omega$ resistor placed in series for R_4 since the lab doesn't have a resistor that's exactly $78k\Omega$.
- We wanted to make sure that everything was working properly before installing the galvanometer, so in its place we connected a $1k\Omega$ resistor going from the potentiometer to ground.
- Once all of this was built, we used a multi-meter to measure the current across the $1k\Omega$ resistor. While measuring the current, we adjusted the potentiometer until we saw 50μA of current across the resistor.
- With the potentiometer set, we were ready to replace the $1k\Omega$ resistor with the galvanometer and test out the final circuit.
- The results seen in the circuit met out expectations: with the input at $0V$, the galvanometer needle remained in its center position. When the input voltage was turned up to 1V, the needle was fully deflected to indicate that 50μA of current was going through the device. Additionally, the circuit never allowed more than 60μA of current to go through the galvanometer, even when the input voltage was greater than $1V$.

3 Voltmeter Design 2

This second design uses a current source to function as a voltmeter. The skeleton circuit for this design is shown in Figure 4

3.1 Choosing the Op-Amp

For this second design, we will be using the same op-amp that we used for the previous circuit. This model was chosen again because the specifications for the second design remain the same as the specifications for the first design, and this op-amp is best suited to meet these specifications.

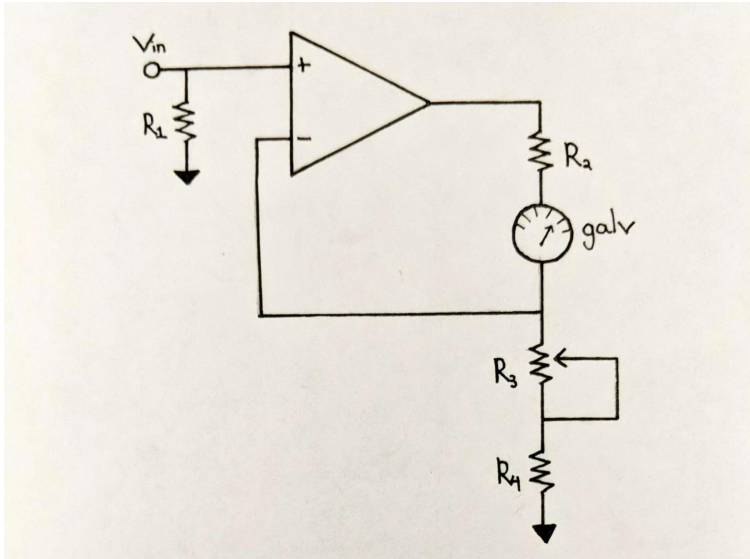

Figure 4: Skeleton Circuit for Design 2

3.2 Choosing the Resistors

Since we are using the same op-amp as the one used in the previous circuit, the difficult part of this design is choosing the values for the resistors.

Similar to design 1, this circuit needs to have an input resistance that is greater than or equal to $1M\Omega$. Because R_1 is the grounded resistor found at the input terminal of the op-amp, it was once again chosen to be $1M\Omega$ in order to meet this specification.

The next step is to find values for R_3 and R_4:

- Since we have a $1V$ input at the positive terminal of the op-amp, $1V$ will be measured at the negative terminal as well. From this we can reason that there has to be $1V$ in between the galvanometer and R_3, since there's nothing but a wire connecting it to the negative terminal of the op-amp.
- Because $1V$ should be measured right before R_3, a $1V$ voltage drop will be seen going from R_3 to R_4 to ground.
- Since $1V$ voltage corresponds to 50μA of current in the specifications, we should see 50μA of current across R_3 and R_4. From this we can reason:

$$1V = (R_3 + R_4)(50\mu A)$$
$$(R_3 + R_4) = \frac{1V}{50\mu A}$$
$$(R_3 + R_4) = 20k\Omega$$

- Because the combined resistance of R_3 and R_4 is $20k\Omega$, we decided to choose a $10k\Omega$ potentiometer for R_3.
- From this we can solve for R_4:

$$R_4 = (R_3 + R_4) - (\frac{R_{3,max}}{2})$$
$$(R_3 + R_4) = 20k\Omega$$
$$\frac{R_{3,max}}{2} = \frac{10k}{2} = 5k\Omega$$
$$R_4 = 20k\Omega - 5k\Omega$$
$$R_4 = 15k\Omega$$

- Using the reasoning above, we chose R_4 to be $15k\Omega$.

The last step before finalizing the design is to find the value of R_2:

- We know that the maximum output voltage from the op-amp is going to be $5V$ (since it's powered by $5V$). This makes the maximum voltage drop across R_2, R_3, R_4, and the galvanometer $5V$.
- Since we need to ensure that no more than 60μA of current goes through the galvanometer, we need to choose resistors so that no more than 55μA of current is seen through the galvanometer.
  - Just like what was done with design 1, we want to solve for a maximum current of 55μA so there is still some room for error. This will make us certain that the current going through the galvanometer will not go over 60μA.
- Using all of our known values, we can solve for R_2:

$$5V = (R_2 + R_3 + R_4 + R_{galv})(55\mu A)$$
$$(R_2 + R_3 + R_4 + R_{galv}) = \frac{5V}{55\mu A} = 91k\Omega$$
$$R_2 = 91k\Omega - (R_3 + R_4) - R_{galv}$$
$$(R_3 + R_4) = 20k\Omega$$
$$R_{galv} = 1k\Omega$$
$$R_2 = 91k\Omega - 20k\Omega - 1k\Omega$$
$$R_2 = 70k\Omega$$

To summarize, the values for the resistors in this circuit are:

- R_1 was chosen to be $1M\Omega$
- R_2 was found to be $70k\Omega$
- R_3 is going to be a $10k\Omega$ potentiometer
- R_4 was found to be $15k\Omega$.

3.3 Building the Circuit

Now that we have chosen the op-amp model and all of the values of our resistors, we are ready to produce a final design of the circuit using these new parameters. The final circuit design for the voltmeter design 2 is shown in Figure 5

With the final design set, we are ready to start building the circuit.

- To build the circuit, we kept the same op-amp from design 1 installed, with the same resistor at the input of the op-amp, and the same power supply hooked up to pins 4 and 7.
- For R_2, we didn't have a $70k\Omega$ resistor available in the lab, so we used one $68k\Omega$ resistor and one $2.2k\Omega$ resistor, making the actual resistance of R_2 $70k\Omega$. These two resistors were placed in series directly at the output (pin 6) of the op-amp.
- In place of the galvanometer, we used a $1k\Omega$ resistor so we can test the circuit without damaging the device. The $1k\Omega$ resistor was connected to the $2.2k\Omega$ resistor.
- The $10k\Omega$ potentiometer was connected to the $1k\Omega$ resistor, and the $15k\Omega$ resistor was connected from the potentiometer to ground.
- To test the circuit and adjust the potentiometer, we hooked up the multi-meter to the $1k\Omega$ resistor and adjusted the potentiometer unwil we saw 50μA of current going through the resistor.
- Finally, we replaced the $1k\Omega$ resistor with the galvanometer. Just like the results we saw in the previous design, the needle remained in the center with a $0V$ input, and fully deflected to the right with a $1V$ input indicating 50μA of current is going through the device.

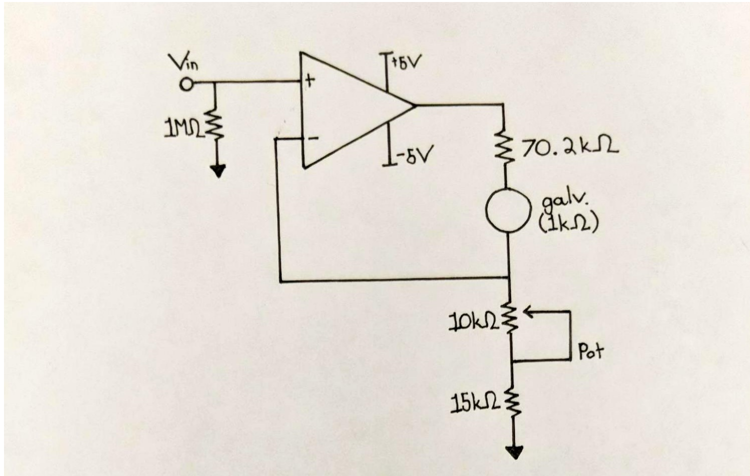

Figure 5: Final Design for Voltmeter Circuit Design 2

4 Conclusions and Results

In both designs, the circuits behaved exactly how we expected them to: the needle on the galvanometer remained in the center when $0V$ was inputed, and deflected all the way to the right with a $1V$ input, indicating that 50μA of current was going through the device. Additionally, neither circuit allowed more than 60μA of current to go through the galvanometer, even when the input voltage was raised above $1V$. This allows us to conclude that both designs properly function as a voltmeter without damaging the galvanometer.