

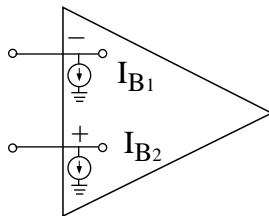


Experiment No. 5. Ideal and Non-Ideal Amplifiers: Part II

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1. Input Bias Currents:

Every amplifier needs an “input bias current” to operate properly. The bias current is the average base current of the input transistors (see data sheets of the LM 741 and LM 380) and is around 0.1 μA. The bias current is small, but is critical for the proper operation of the op-amp, and the design must provide a DC current path to the input terminals. The (+) and (-) input bias currents should be identical but process variation in the fabrication of the amplifier result in a small difference between the input currents. This is called the “input offset current” and is around 20 nA for the LM 741. The model of a real amplifier becomes:

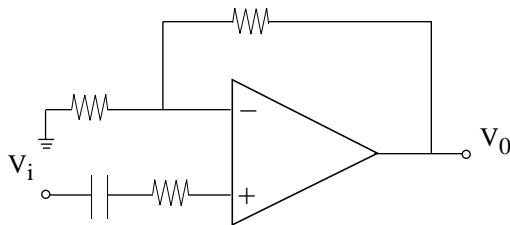


$$I_B = \frac{I_{B1} + I_{B2}}{2}$$

$$I_{OS} = |I_{B1} - I_{B2}|$$

It is easy not to pay attention to the input bias current and design an op-amp which will never work in practice. Listed below are some of these circuits:

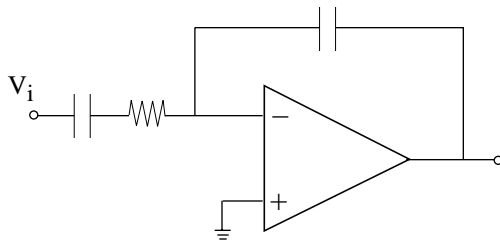
1) Non-Inverting Amplifier:



No DC current in (+) terminal.



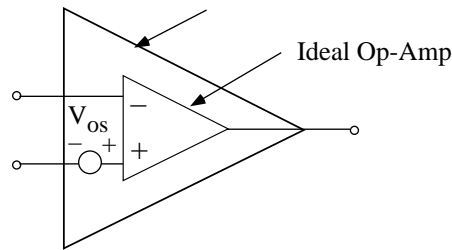
2) Integrator:



No DC current in (-) terminal.

2. Input Offset Voltage:

Again, look at the schematic of the LM 741. The (+) input DC voltage, pin 3, and the (-) input DC voltage, pin 2, are the summation of the DC voltage drop across transistors (Q1, Q3, Q5) and the 1 kΩ resistor and transistors (Q2, Q4, Q6) and the 1 kΩ resistor, respectively. If the fabrication process is perfect, the (+) and (-) DC voltage should be identical. However, due to process variations, there is a small “input offset voltage” between these two terminals and is around 1 mV for the LM 741. The model of an amplifier becomes:

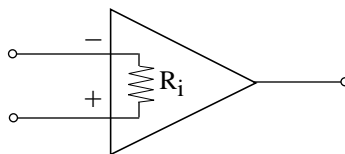


Fortunately, one can eliminate this offset voltage by connecting a 10 kΩ potentiometer between the offset null inputs and $-V_{CC}$ (see data sheets of LM 741). The pin numbers depend on the package; for LM 747, use #3 and #14.

3. Input Resistance:

The input resistance of an ideal amplifier is infinite, i.e., the amplifier does not load the previous circuit. In a real op-amp, the input resistance is high, around 2 MΩ (typical) for the LM 741 and 150 KΩ for the LM 380. In most cases, the input resistance does not affect the operation of a circuit. However, if very high resistances (0.5 MΩ or higher) are used in the feedback path of the LM 741 or if the source impedance is very high (100's of KΩ), then the input resistance should be taken into account in the AC circuit analysis.

There are special op-amps with input resistances of 100 MΩ or higher. These op-amps are made for sensors having a very high source resistance (around 1-10 MΩ) such as piezoelectric transducers.





4. Common-Mode Rejection Ratio:

An ideal amplifier should only respond to the difference between the (+) and (-) input voltages with a gain A. However, in a real op-amp, if the same voltage is applied to (+) and (-) terminals, we do find a small output voltage. This is called “common-mode” operation.

The output of a real amplifier is therefore:

$$V_0 = \underbrace{A}_{\text{Difference Gain}} \cdot \underbrace{(V_1 - V_2)}_{\text{Difference Signal}} + \underbrace{A_{cm}}_{\text{Common-Mode Gain}} \cdot \underbrace{\left(\frac{V_1 + V_2}{2}\right)}_{\text{Common-Mode Signal}}$$

The common-mode rejection ratio (CMRR) is defined as:

$$CMRR = \frac{A}{A_{cm}} \quad (\text{unitless})$$

$$CMRR(dB) = 20 \log (CMRR) = 20 \log \left(\frac{A}{A_{cm}} \right)$$

$$= A(dB) - A_{cm}(dB)$$

and describes the ability of the op-amp to discriminate against common-mode signals (which are typically noise dominated). The CMRR of the LM 741 is 90 dB. This means that if the 741 is designed for a differential voltage gain of A = 100 (40 dB), it will have a gain of A_{cm} = 0.0032 (-50 dB) for any common-mode signals. The CMRR is an essential specification for noisy environments, and it is typical to have a CMRR of 120⁺dB for instrumentation/sensor/precision-type amplifiers.



Experiment No. 5. Noise and Differential Amplifiers to the Rescue

Noise is the enemy of the circuit designer. Amplifiers can break into oscillations, low-level signals can be lost forever and an audio signal can be unbearable to hear in high noise conditions. Noise is generated everywhere around you! If you are in the lab, just look above you and notice the fluorescent light bulbs. These bulbs turn on and off 120 times a second (120 Hz) and generate 120 Hz noise (and harmonics too!). Look now at the Agilent rack with all the digital processors inside for the display/decision circuitry or the CAEN Lab down the corridor with the hundred Agilent and Sun workstations. These digital circuits are running on 10-200 MHz square waves which, if coupled to your circuit (even at 1 mV – 1 μ V levels), will be considered as noise. You also have 3 elevators in the building, and huge cooling and warming units on the 5th floor. These AC units run on 480 V and can switch up to 100's of Amperes. Some of them even run at 360 Hz (and not 60 Hz) for efficient operation. Anytime a motor/heater/fan/... turns on or off, it will switch 10-100 A in 100-2000 ms. As seen in class, a very narrow square-wave (or a pulse) has a large number of harmonics, and for this level of current/voltage, you can measure the noise harmonics up to the hundred of kHz range!

Broadly defined, noise is any unwanted electrical signal at any frequency which enters your circuit. The reason why a square-wave switching in a computer or a 50 A current switching in a motor affects your circuit is because of ... RADIATION. (You will study radiation in EECS 230 and 330.) The AC wires of the motor, the cables of the computer, ... act as antennas (although inefficient ones) and radiate a small part of the signal and its harmonics. The reason why it is detected in your circuit is that your circuit wires also act as tiny antennas and receive these noise signals! The signal can enter through the bias supply lines (most common problem) or through the wiring of the circuit (common problem). It is therefore important to wire a circuit properly (as discussed in lectures) so as to minimize noise pick-up.

Some of the rules are:

1. Use the shortest possible wiring connections. Do not make big loops in the air.
2. Twist your power supply and input cables around each other. Use coaxial cables for low level input voltages (μ V).
3. Use many ground-plane lines/areas around your circuit and connect them together. Do not use a single ground node for the whole circuit.
4. Put your circuit in a metal box and ground the box.

The largest sources of man-made noise in our daily lives are:

1. The 120-480 V 60 Hz AC system carrying tens of 1,000's of amperes and powering thousands of units (fridges, motors, fans, heaters, ...) which turn on and off quite frequently. This noise extends up to 10's and 100's of kHz.
2. The automobile and all engines with spark-plugs. It takes a 10-20 kV voltage pulse to ignite a spark in the piston and this is happening at 3000 turns/minute (Ahhhh!). The electrical noise of a car extends up to the MHz range.
3. Computers and digital switching equipment. There are so many of them and they are so close to measurements labs. This noise extends to the 100 MHz region with the new computer clocks.



The noise levels could be as low as 1 nV in well wired/shielded circuits and far-away from man-made noise, to μV levels in typical circuits, to mV levels next to equipment and badly wired circuits, to even Volt levels next to large motors and transformer stations with 100's A currents. In most cases, noise does not affect digital circuits operating at 5 V, but it can seriously deteriorate analog circuits operating in the sub-mV levels.

Note that while you can nearly eliminate noise pick-up with proper circuit wiring and shielding, you can never eliminate the noise which is generated by the electronic components themselves (resistors, transistors, diodes, op-amps, ...) within your circuit! Fortunately, the electronic component noise is well understood and is at a pretty low level (around $1\text{ nV}/\sqrt{\text{Hz}}$ or $5\text{ pA}/\sqrt{\text{Hz}}$).

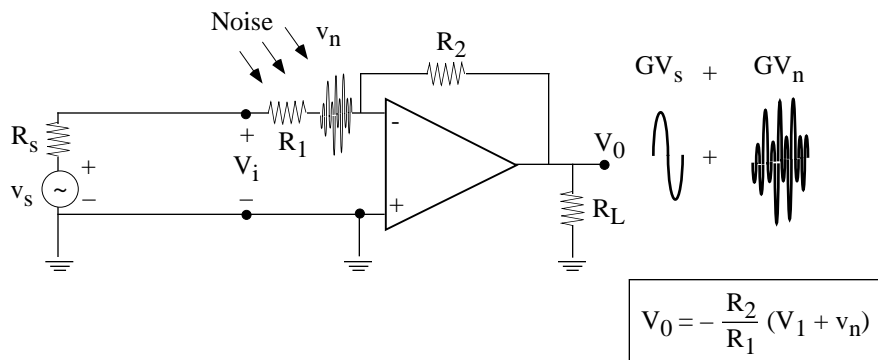
Noise in Nature:

Imagine now a world having not a single man-made electrical apparatus! Do we still have electrical noise? The answer is ... absolutely! Nature is full of charged particles creating electrical storms and lightning. The noise generated by lightning is very large up to 10 MHz, and since there is always some lightning somewhere in the world, we will always measure a large noise voltage. If one has a good antenna which couples well to radiation, one can easily measure a noise voltage as high as $0.1-1\mu\text{V}/\sqrt{\text{Hz}}$ even if the lightning is over Brazil (I am serious!). If you have a system with a bandwidth of 4 kHz, the total noise voltage can be as high as 6-60 μV.

Between 30 MHz and 800 MHz, Galactic noise dominates our world outside cities and suburban areas. It is the noise generated by the random movement of charged regions in our sun, solar system and distant stars/galaxies. It is true that these noise sources are very far away, but on the other hand, they are very, very large regions (many times the size of our earth/solar-system to say the least). The noise level is low, around $2-20\text{ nV}/\sqrt{\text{Hz}}$. For a system bandwidth of 4 kHz, the total noise voltage is around 0.2-1 μV. The Galactic noise tapers off at 800 MHz and becomes the background cosmic radiation noise, which is the remnant of the big-bang explosion. This noise is equivalent to the noise generated by a resistor immersed in a 3K liquid. It is around $0.1-0.2\text{ nV}/\sqrt{\text{Hz}}$ at any frequency above 800 MHz.

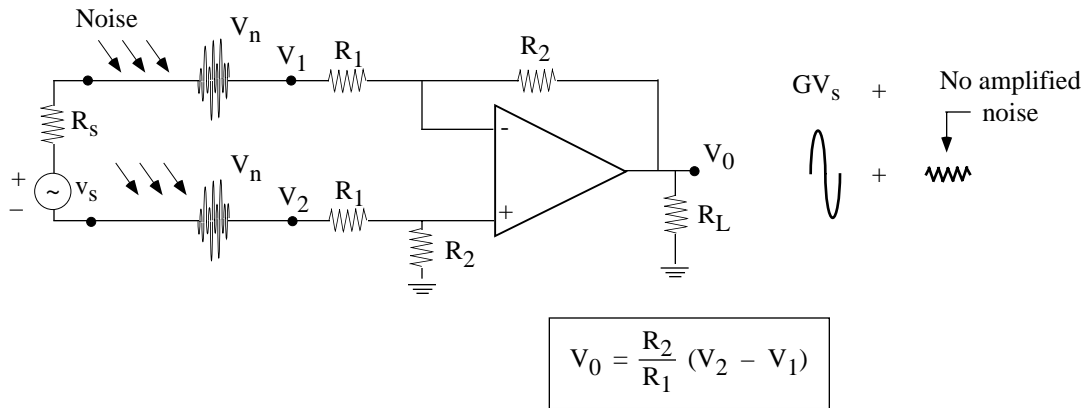
Differential vs. Single-Ended Amplifiers:

Consider the audio amplifier designed and tested in Lab #3. One input line is connected to non-inverting input and the other input line is grounded. This is called a single-ended amplifier. When noise couples to the input lines, it couples to both lines equally. In this case, one line is grounded and the noise voltage is immediately shorted to zero. However, the noise voltage in the signal line will be amplified with the same gain as the signal. If the signal is in the μV range, and the noise is in the μV-mV range, this could lead to a very noisy output.





Single-ended amplifiers are therefore useless in noisy environments with low signal levels. One way to solve this problem is to use a differential amplifier. The configuration of a differential amplifier is shown below:



Now, due to noise coupled into the circuit:

$$V_1 = \frac{+V_s}{2} + V_n \quad \text{and} \quad V_0 = \frac{R_2}{R_1} (V_2 - V_1) = \frac{R_2}{R_1} (-V_s + V_n - V_n) = \frac{-R_2}{R_1} (V_s)$$

$$V_2 = \frac{-V_s}{2} + V_n$$

Basically, any signal which appears on both lines equally (such as a noise signal) will be rejected by the differential amplifier.



APPLICATION AREAS OF DIFFERENTIAL AMPLIFIERS:

The differential amplifier is perfectly suited for low-level signal amplification in noisy environments. The most common application areas are:

1. Automotive Sensors: There are many sensors in the engine block which monitor the temperature and pressure of each cylinder and feed the data to the ignition-timing computer. The sensors generate voltage levels in the mV range (1-100 mV) next to 10-20 kV spark-plug voltages (Ahhh!). Differential amplifiers are used to eliminate the spark-plug and engine noise. In these conditions, it would be impossible to have a working circuit in an engine block with a single-ended amplifier.
2. Biomedical Sensors: The medical field uses an array of biomedical sensors to monitor the temperature, pressure, fluid flow, etc. in the body, especially for the heart (EKG – Electro-cardiogram) and the brain. The sensors generate low voltage levels (mV range) and are placed in an electrical “noisy” environment, which is the body and the nervous system (see Chapter 6 in the additional course notes). Differential amplifiers are therefore used to amplify the sensor voltages and eliminate the noise.
3. Accelerometers, Pressure Meters, Temperature Meters, etc.: Most environmental sensors, in automotive, office, factory, home, ... generate low-level voltages (μV -mV). Differential amplifiers are used to amplify the signal and make them immune to the surrounding noise.
4. Audio Electronics: Differential amplifiers are used as pre-amps for high-quality microphones (μV -mV levels) and for phone cartridges (μV -100 mV levels).
5. Instrumentation Equipment: Very sensitive instrumentation in the lab capable of detecting nV level voltages use exclusively differential amplifiers in their input stages. The differential amplifiers can reduce the noise pickup by 60-80 dB resulting in an accurate voltmeter capable of detecting 1 nV!



Experiment No. 5. Differential Amplifiers; Differential Temperature Sensor

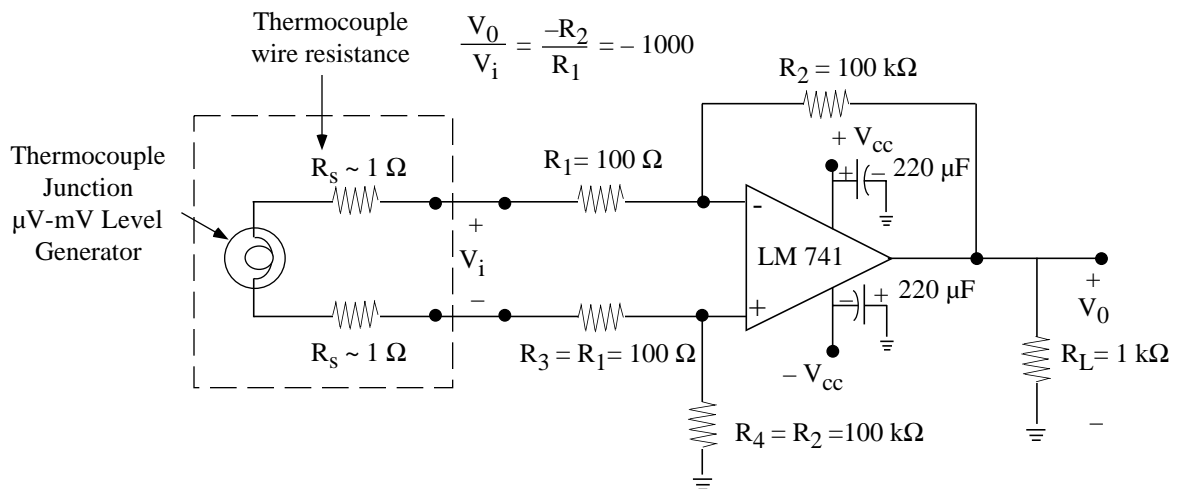
Goal: The goal of Experiment #5 is to build and test a low-noise differential amplifier and determine its V_{OS} , I_b and CMRR. Also, to build and test a sensitive temperature meter using a mV-level thermocouple sensor.

- Read this experiment and answer the pre-lab questions before you come to the lab.

5.1 Differential Amplifier and Common-Mode Rejection Ratio:

- Equipment:**
- Agilent E3631A Triple output DC power supply
 - Agilent 33120A Function Generator
 - Agilent 34401A Multimeter
 - Agilent 54645A Oscilloscope

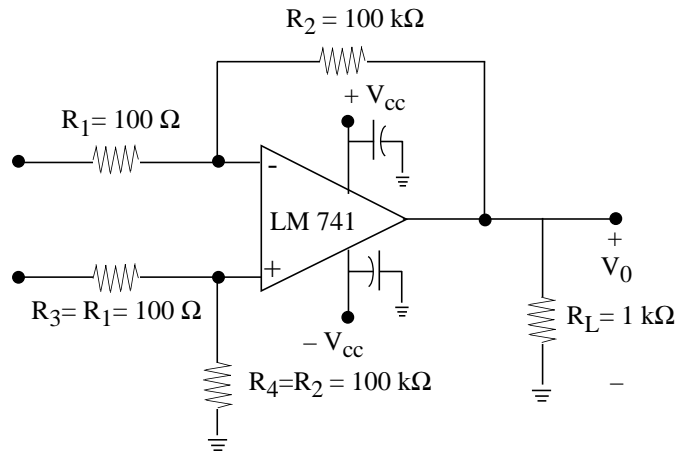
A differential amplifier suitable as a high-gain thermocouple amplifier is shown below:



- Draw the circuit in your notebook.
- Measure exactly R_1 , R_2 , R_3 and R_4 . You will need this for your lab report.
- Carefully connect the op-amp. Remember that you have LM 741 in the LM 747 package. Refer to pin numbers on p. 54 of this Manual. Take your time, ask your lab instructor for help if needed, and make sure that the connections are clean with ample space for probing.
- Since the power supply leads act as antennas for noise, it is important to put two capacitors between the supply lines and ground. A capacitor value of 200 μF is more than enough for most noise problems. Please pay attention to the orientation of the electrolytic capacitors (200 μF). Wrongly connected electrolytic capacitors may explode!
- Assemble the circuit on the breadboard. Do not connect the thermocouple yet! Leave an open circuit across the input nodes (across V_i). Connect the circuit board to the power supply, but do not apply the voltage yet. Show your completed circuit to your lab instructor before applying voltage from the Agilent power supply.



The circuit becomes:



First of all, check whether your circuit works as an amplifier. Apply a sinusoidal signal at 1 kHz and 100 mV ppk from the function generator to the inverting input of your amplifier (through the input resistor R_1). Since the gain of your amplifier is about 1000, the expected output voltage is 100 V ppk. However, your power supply is set at +12 V and -12 V; thus the output signals will be clipped at about 20 V ppk. On the screen of your scope you will see an input sine wave and a badly clipped output, resembling a square wave. Make sure that V_{out} , ppk is about 20V. For this particular circuit this indicates correct operation. Now connect the (+) input of your amplifier (through the input resistor R_3) to the (-) input. The signal from your function generator becomes a common-mode signal and is therefore greatly suppressed; it may even look as a flat line. Increase the input to 1 Vpk, adjust **Volts/Div** in both channels, and measure Vppk of the output signal. It should be less than 300 mVppk. If your common-mode output signal is smaller than 300 mVppk, everything is fine. If your output is larger, call your lab instructor for help.

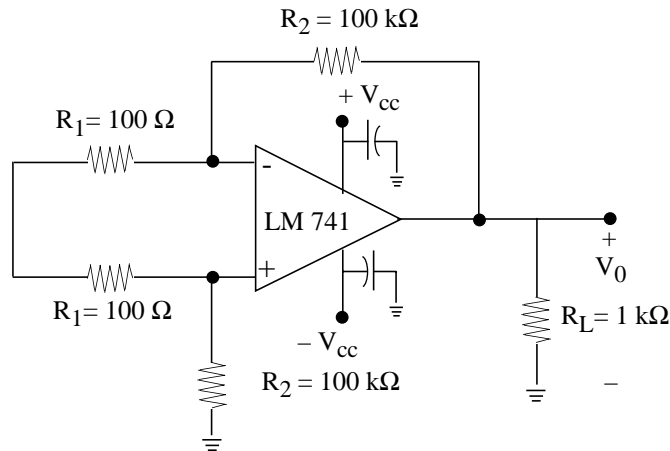
After you've checked that your amplifier works, disconnect the signal from the function generator, disconnect the two inputs from each other, and start doing the measurements.

- 6. Measure the DC output voltage (V_o) and the DC voltages at the V^+ and V^- terminals.

As shown in your pre-lab, this measurement gives the input bias current of the op-amp knowing V^+ and R_4 .



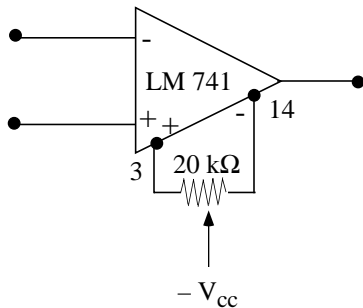
7. Connect a short circuit across the input. The circuit becomes:



8. Measure the DC output voltage (V_0) and the DC voltages at the V^+ and V^- terminals.

As shown in your pre-lab, this measurement results primarily in the input offset voltage of the op-amp.

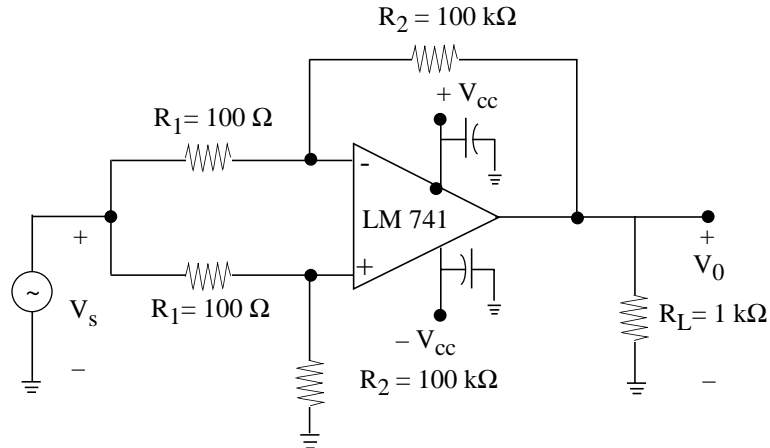
9. Keep the short circuit at the input and connect a 10 kΩ or 20 kΩ Pot. between the negative offset pin (pin #3) and positive offset pin (pin #14) and to $-V_{CC}$ as indicated below. This pot balances the input bias voltage and reduces V_0 to ~ 0 V. Adjust the pot until $|V_0| < 0.1$ V and as close to zero as you can get it.



Pin configuration is for the LM 747 package of page 58.

You have now corrected for the effects of the input offset voltage (which is the dominant effect).

10. Set the Agilent 33120A signal generator to give a 200 Hz signal with $V_{ppk} = 4$ V. Connect it to the common input node V_i . Make sure that the offset voltage of the Agilent 33120A signal generator is zero. The common-mode circuit becomes:



11. Measure V_O (V_{avg} and V_{ppk}). Knowing that the differential signal gain of this amplifier is $A = 1000$ at 200 Hz, calculate in dB the CMRR ($= A/A_{(com)}$).
12. The CMRR is dependent on the input offset voltage balance. Using the 20 K Ω pot, purposely adjust the DC output voltage in the range of $|5\text{ V}|$ and measure V_O (V_{avg} and V_{ppk}) for a 200 Hz signal with $V_{ppk} = 4\text{ V}$. Calculate the CMRR.
13. Remove the AC source (but keep the short circuit) and adjust the pot again until $|V_O| < 0.1\text{ V}$ and as close to zero as you can get it.

5.2 Thermocouple Measurements:

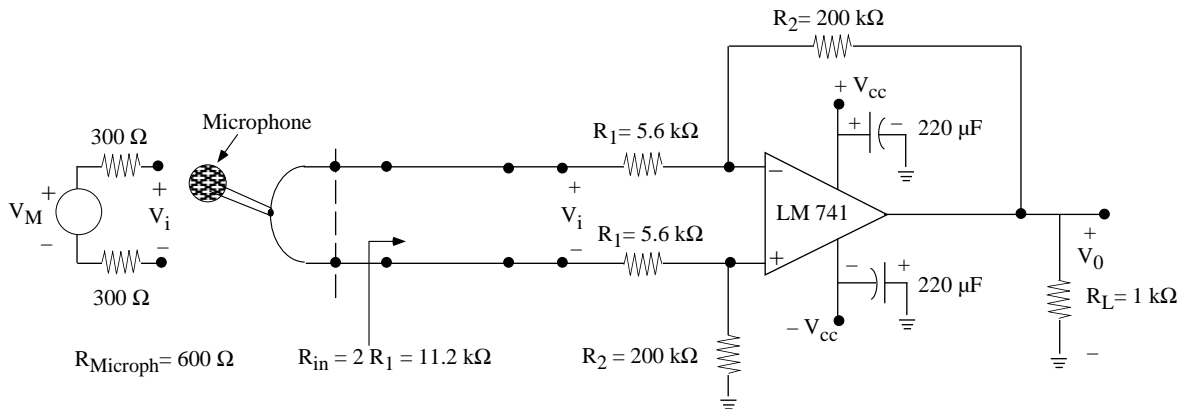
1. Connect the thermocouple to the input circuit, making sure to remove the short-circuit connection at the input. At room temperature (22-25°C), both hot and cold tips of the thermocouple at nearly at the same temperature.
 - Zero the multimeter now using the null key (optional). Record the small mV reading at room temperature.
2. Hold the thermocouple between your fingers. Determine the temperature from the measured output voltage (V_O) and the table given at the end of this experiment. Is this your true body temperature? Explain.
3. Fill a styrofoam cup with cold water with ice and dip the tip of the thermocouple in the cup. The temperature of ice/water mixture is 0°C by definition. This measurement provides a reference point for all other measurements. Use the V_O of the ice/water mixture to find the room temperature.
4. Fill a styrofoam cup with hot water and determine its temperature.

Congratulations, you have built a very sensitive high-gain (1000) differential amplifier suitable for sensor applications.



Application: Microphone Pre-Amplifiers

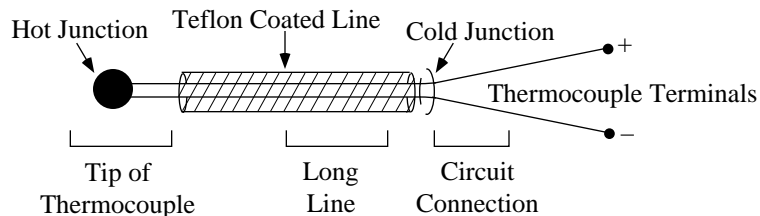
A hi-fi differential audio amplifier suitable for a 600 Ω microphone is shown below. This is called a “mic pre-amp” in audio terminology. The amplifier input impedance is chosen to be 11.2 kΩ so as not to load the microphone ($V_i/V_M = 0.95$). The amplifier gain is (30 dB) which results in a 44 kHz bandwidth for the LM 741 op-amp.



$$\frac{V_i}{V_M} = \frac{2R_1}{2R_1 + R_M} = 0.95, \quad \left| \frac{V_0}{V_i} \right| = \frac{200}{5.6} = 35.7 \Rightarrow \frac{V_0}{V_M} = 34 \approx 30.6 \text{ dB}$$

What are Thermocouples?

The thermocouple is a temperature sensor composed of two different metals. It results in a small output voltage (mV range) which depends on the temperature difference between the “hot” junction and the “cold” junction. The thermocouple used in EECS 210 is composed of an Iron:Constantanium (Copper-Nickel) junction and delivers ~0.5 mV for a temperature difference of 10°C. The junction voltage vs. temperature difference is presented in the table on p. 78. This thermocouple is very similar to the units which measure the engine temperature in a car, or the internal body temperature (oral or rectum). The output voltage is so low (–4 mV to +5 mV) that a high-gain (1000) differential amplifier is needed for noise immunity. NOTICE, THE THERMOCOUPLE TERMINALS ARE NOT CONNECTED TO GROUND, so it is a true differential voltage source.





Thermocouple Output Voltage in Absolute Millivolts versus Temperature Difference in °C

Type J – Iron:Constantanum (Copper-Nickel)

| | | | | | | | | | | | | |
|-------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--|
| -210 | -8.096 | | | | | | | | | | | |
| -200 | -7.890 | -7.912 | -7.934 | -7.955 | -7.976 | -7.996 | -8.017 | -8.037 | -8.057 | -8.076 | -8.096 | |
| -190 | -7.659 | -7.683 | -7.707 | -7.731 | -7.755 | -7.778 | -7.801 | -7.824 | -7.846 | -7.868 | -7.890 | |
| -180 | -7.402 | -7.429 | -7.455 | -7.482 | -7.508 | -7.533 | -7.559 | -7.584 | -7.609 | -7.634 | -7.659 | |
| -170 | -7.122 | -7.151 | -7.180 | -7.209 | -7.237 | -7.265 | -7.293 | -7.321 | -7.348 | -7.375 | -7.402 | |
| -160 | -6.821 | -6.852 | -6.883 | -6.914 | -6.944 | -6.974 | -7.004 | -7.034 | -7.064 | -7.093 | -7.122 | |
| -150 | -6.499 | -6.532 | -6.565 | -6.598 | -6.630 | -6.663 | -6.695 | -6.727 | -6.758 | -6.790 | -6.821 | |
| -140 | -6.159 | -6.194 | -6.228 | -6.263 | -6.297 | -6.331 | -6.365 | -6.399 | -6.433 | -6.466 | -6.499 | |
| -130 | -5.801 | -5.837 | -5.874 | -5.910 | -5.946 | -5.982 | -6.018 | -6.053 | -6.089 | -6.124 | -6.159 | |
| -120 | -5.426 | -5.464 | -5.502 | -5.540 | -5.578 | -5.615 | -5.653 | -5.690 | -5.727 | -5.764 | -5.801 | |
| -110 | -5.036 | -5.076 | -5.115 | -5.155 | -5.194 | -5.233 | -5.272 | -5.311 | -5.349 | -5.388 | -5.426 | |
| -100 | -4.632 | -4.673 | -4.714 | -4.755 | -4.795 | -4.836 | -4.876 | -4.916 | -4.956 | -4.996 | -5.036 | |
| -90 | -4.215 | -4.257 | -4.299 | -4.341 | -4.383 | -4.425 | -4.467 | -4.508 | -4.550 | -4.591 | -4.632 | |
| -80 | -3.785 | -3.829 | -3.872 | -3.915 | -3.958 | -4.001 | -4.044 | -4.087 | -4.130 | -4.172 | -4.215 | |
| -70 | -3.344 | -3.389 | -3.433 | -3.478 | -3.522 | -3.566 | -3.610 | -3.654 | -3.698 | -3.742 | -3.785 | |
| -60 | -2.892 | -2.938 | -2.984 | -3.029 | -3.074 | -3.120 | -3.165 | -3.210 | -3.255 | -3.299 | -3.344 | |
| -50 | -2.431 | -2.478 | -2.524 | -2.570 | -2.617 | -2.663 | -2.709 | -2.755 | -2.801 | -2.847 | -2.892 | |
| -40 | -1.960 | -2.008 | -2.055 | -2.102 | -2.150 | -2.197 | -2.244 | -2.291 | -2.338 | -2.384 | -2.431 | |
| -30 | -1.481 | -1.530 | -1.578 | -1.626 | -1.674 | -1.722 | -1.770 | -1.818 | -1.865 | -1.913 | -1.960 | |
| -20 | -0.995 | -1.044 | -1.093 | -1.141 | -1.190 | -1.239 | -1.288 | -1.336 | -1.385 | -1.433 | -1.481 | |
| -10 | -0.501 | -0.550 | -0.600 | -0.650 | -0.699 | -0.748 | -0.798 | -0.847 | -0.896 | -0.945 | -0.995 | |
| 0 | 0.000 | -0.050 | -0.101 | -0.151 | -0.201 | -0.251 | -0.301 | -0.351 | -0.401 | -0.451 | -0.501 | |
| DEG C | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | |
| 0 | 0.000 | 0.050 | 0.101 | 0.151 | 0.202 | 0.253 | 0.303 | 0.354 | 0.405 | 0.456 | 0.507 | |
| 10 | 0.507 | 0.558 | 0.609 | 0.660 | 0.711 | 0.762 | 0.813 | 0.865 | 0.916 | 0.967 | 1.019 | |
| 20 | 1.019 | 1.070 | 1.122 | 1.174 | 1.225 | 1.277 | 1.329 | 1.381 | 1.432 | 1.484 | 1.536 | |
| 30 | 1.536 | 1.588 | 1.640 | 1.693 | 1.745 | 1.797 | 1.849 | 1.901 | 1.954 | 2.006 | 2.058 | |
| 40 | 2.058 | 2.111 | 2.163 | 2.216 | 2.268 | 2.321 | 2.374 | 2.426 | 2.479 | 2.532 | 2.585 | |
| 50 | 2.585 | 2.638 | 2.691 | 2.743 | 2.796 | 2.849 | 2.902 | 2.956 | 3.009 | 3.062 | 3.115 | |
| 60 | 3.115 | 3.168 | 3.221 | 3.275 | 3.328 | 3.381 | 3.435 | 3.488 | 3.542 | 3.595 | 3.649 | |
| 70 | 3.649 | 3.702 | 3.756 | 3.809 | 3.863 | 3.917 | 3.971 | 4.024 | 4.078 | 4.132 | 4.186 | |
| 80 | 4.186 | 4.239 | 4.293 | 4.347 | 4.401 | 4.455 | 4.509 | 4.563 | 4.617 | 4.671 | 4.725 | |
| 90 | 4.725 | 4.780 | 4.834 | 4.888 | 4.942 | 4.996 | 5.050 | 5.105 | 5.159 | 5.213 | 5.268 | |
| 100 | 5.268 | 5.322 | 5.376 | 5.431 | 5.485 | 5.540 | 5.594 | 5.649 | 5.703 | 5.758 | 5.812 | |
| 110 | 5.812 | 5.867 | 5.921 | 5.976 | 6.031 | 6.085 | 6.140 | 6.195 | 6.249 | 6.304 | 6.359 | |
| 120 | 6.359 | 6.414 | 6.468 | 6.523 | 6.578 | 6.633 | 6.688 | 6.742 | 6.797 | 6.852 | 6.907 | |
| 130 | 6.907 | 6.962 | 7.017 | 7.072 | 7.127 | 7.182 | 7.237 | 7.292 | 7.347 | 7.402 | 7.457 | |
| 140 | 7.457 | 7.512 | 7.567 | 7.622 | 7.677 | 7.732 | 7.787 | 7.843 | 7.898 | 7.953 | 8.008 | |
| 150 | 8.008 | 8.063 | 8.118 | 8.174 | 8.229 | 8.284 | 8.339 | 8.394 | 8.450 | 8.505 | 8.560 | |
| 160 | 8.560 | 8.616 | 8.671 | 8.726 | 8.781 | 8.837 | 8.892 | 8.947 | 9.003 | 9.058 | 9.113 | |
| 170 | 9.113 | 9.169 | 9.224 | 9.279 | 9.335 | 9.390 | 9.446 | 9.501 | 9.556 | 9.612 | 9.667 | |
| 180 | 9.667 | 9.723 | 9.778 | 9.834 | 9.889 | 9.944 | 10.000 | 10.055 | 10.111 | 10.166 | 10.222 | |
| 190 | 10.222 | 10.277 | 10.333 | 10.388 | 10.444 | 10.499 | 10.555 | 10.610 | 10.666 | 10.721 | 10.777 | |
| 200 | 10.777 | 10.832 | 10.888 | 10.943 | 10.999 | 11.054 | 11.110 | 11.165 | 11.221 | 11.276 | 11.332 | |
| 210 | 11.332 | 11.387 | 11.443 | 11.498 | 11.554 | 11.609 | 11.665 | 11.720 | 11.776 | 11.831 | 11.887 | |
| 220 | 11.887 | 11.943 | 11.998 | 12.054 | 12.109 | 12.165 | 12.220 | 12.276 | 12.331 | 12.387 | 12.442 | |
| 230 | 12.442 | 12.498 | 12.553 | 12.609 | 12.664 | 12.720 | 12.776 | 12.831 | 12.887 | 12.942 | 12.998 | |
| 240 | 12.998 | 13.053 | 13.109 | 13.164 | 13.220 | 13.275 | 13.331 | 13.386 | 13.442 | 13.497 | 13.553 | |
| 250 | 13.553 | 13.608 | 13.664 | 13.719 | 13.775 | 13.830 | 13.886 | 13.941 | 13.997 | 14.052 | 14.108 | |
| 260 | 14.108 | 14.163 | 14.219 | 14.274 | 14.330 | 14.385 | 14.441 | 14.496 | 14.552 | 14.607 | 14.663 | |
| 270 | 14.663 | 14.718 | 14.774 | 14.829 | 14.885 | 14.940 | 14.995 | 15.051 | 15.106 | 15.162 | 15.217 | |
| 280 | 15.217 | 15.273 | 15.328 | 15.383 | 15.439 | 15.494 | 15.550 | 15.605 | 15.661 | 15.716 | 15.771 | |
| 290 | 15.771 | 15.827 | 15.882 | 15.938 | 15.993 | 16.048 | 16.104 | 16.159 | 16.214 | 16.270 | 16.325 | |
| 300 | 16.325 | 16.380 | 16.436 | 16.491 | 16.547 | 16.602 | 16.657 | 16.713 | 16.768 | 16.823 | 16.879 | |
| 310 | 16.879 | 16.934 | 16.989 | 17.044 | 17.100 | 17.155 | 17.210 | 17.266 | 17.321 | 17.376 | 17.432 | |
| 320 | 17.432 | 17.487 | 17.542 | 17.597 | 17.653 | 17.708 | 17.763 | 17.818 | 17.874 | 17.929 | 17.984 | |
| 330 | 17.984 | 18.039 | 18.095 | 18.150 | 18.205 | 18.260 | 18.316 | 18.371 | 18.426 | 18.481 | 18.537 | |
| 340 | 18.537 | 18.592 | 18.647 | 18.702 | 18.757 | 18.813 | 18.868 | 18.923 | 18.978 | 19.033 | 19.089 | |

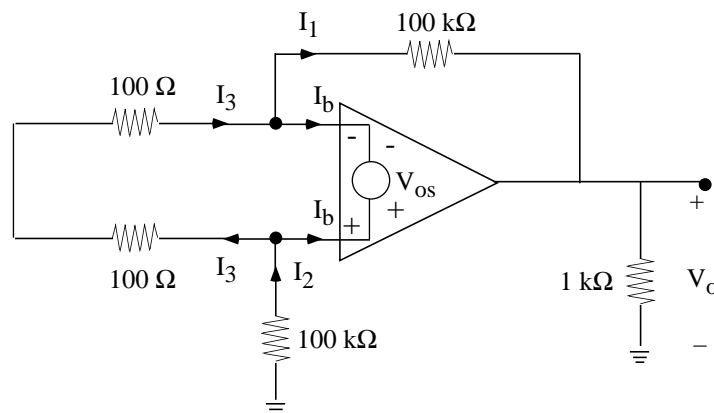
Data obtained from NIST (National Institute for Standards and Technology)



Experiment No. 5. Differential Amplifiers; Differential Temperature Sensor

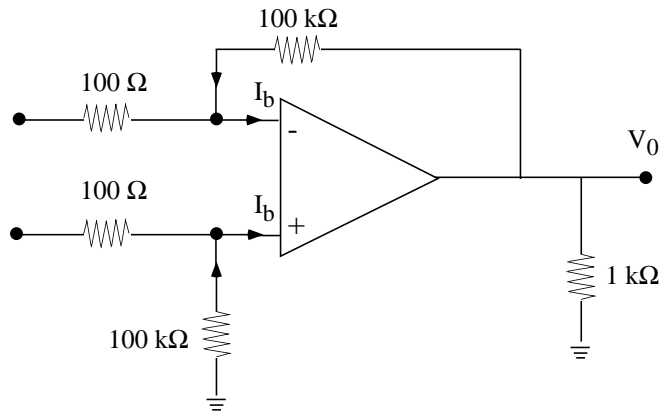
Pre-Lab Assignment

1. Using superposition, calculate V_O/V_i for the thermocouple differential amplifier. Knowing the gain V_O/V_i , predict the 3-dB bandwidth using the 741 op-amp. Is this bandwidth sufficient for temperature measurements?
2. An amplifier has a midband gain of 400 and a CMRR of 100 dB. Calculate the output voltage (ppk) if a 2 V_{ppk} common-mode signal is applied to its input.
3. An amplifier with a very high gain (1000) such as the thermocouple amplifier is very sensitive to the input bias current or input voltage offset. Consider this circuit with $V_O/V_i \approx -1000$.
 - a. One way to measure V_O effect (V_{OS}) is to put a short circuit at the input and measure V^+ , V^- and V_O . Assume that due to the input voltage offset there is a 3 mV difference between V^- and V^+ ($V^+ - V^- = V_{OS} = 3$ mV).
 - Calculate I_3 (neglect 1Ω resistances).
 - Calculate I_2 and I_1 ($I_b = 0.1 \mu A$).
 - Knowing I_2 and ΔV , calculate V^+ (with respect to ground) and V^- .
 - Knowing V^- and I_1 , calculate V_O (you will find a large V_O !).





- b. One way to measure the input bias currents is to put an open circuit at the input and measure V^+ . Calculate I_b if $V^+ = -6 \text{ mV}$.



(Be careful: The input offset voltage (V_{OS}) still exists and it is the one which is dominant and determines V_0 . So the measurement at V^+ only gives the bias currents).

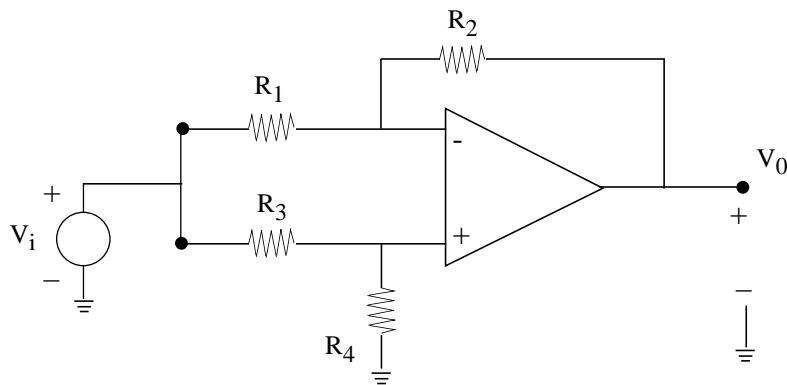
- c. Is it possible to determine accurately V_{OS} if a voltmeter is connected in parallel with the (+) and (-) op-amp terminals? Why?
- 4. Using the thermocouple data, plot the response for $-20^\circ\text{C} < \Delta T < +20^\circ\text{C}$ (choose few points only). Determine the slope ($\text{mV}/^\circ\text{C}$) of the sensor. If the measured output voltage (V_0) from the differential amplifier has an accuracy of $\pm 20 \text{ mV}$, determine the accuracy in the measured input temperature. Make the plot with MATLAB. Use markers to show each data point.



Experiment No. 5. Differential Amplifiers; Differential Temperature Sensor

Lab-Report Assignment

- Knowing your DC voltage measurements with a *short-circuit* at the input, calculate V_{OS} .
 - Knowing your V^+ DC measurement with an *open-circuit* at the input, calculate I_D .
- What is the measured CMRR at 200 Hz and for a $|V_O| \approx 0$ V and $|V_O| \approx 5$ V? The op-amp gain is 1000. You will see that the op-amp has the highest CMRR for a near-zero input offset.
- One can argue that the measured common-mode output voltage is due to the small differences between R_1 , R_2 , R_3 , R_4 . To prove them wrong, consider this circuit:



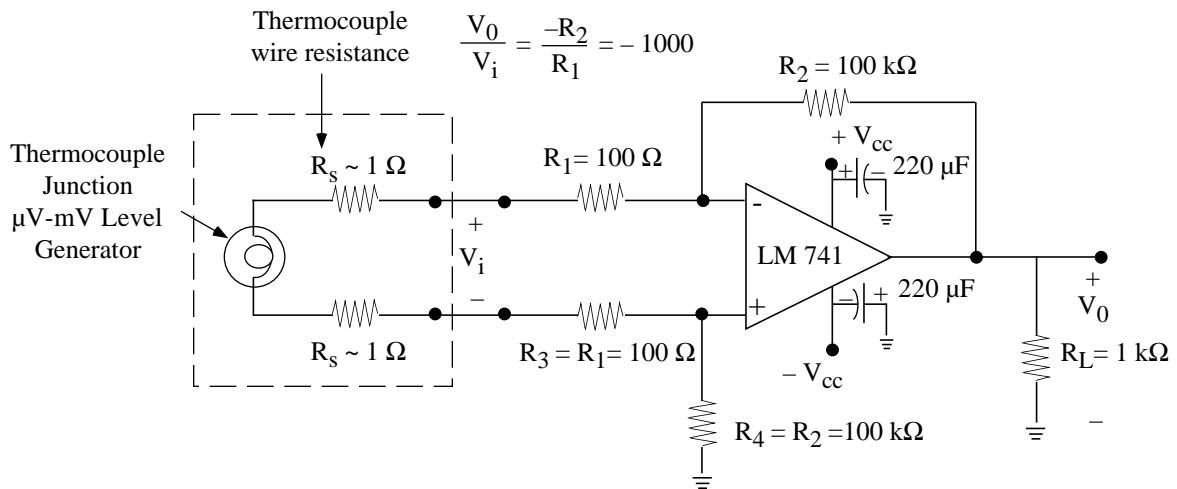
- Using the Golden Rules and the principle of Superposition (if you wish), calculate V_O/V_i .
 - Make sure that your expression reduces to $V_O = 0$ when $R_3 = R_1$ and $R_4 = R_2$.
 - For $R_1 = 102 \Omega$, $R_3 = 103 \Omega$, $R_2 = 99,016 \Omega$ and $R_4 = 98,688 \Omega$ (I measured these values in my experiment), calculate V_O for $V_i = 2$ V_{ppk}. I measured $V_O = 180$ mV_{ppk} for $V_i = 2$ V_{ppk} and a CMRR of 81 dB. What is the contribution of the resistances inequalities to V_O in V and dB? Do you think that the slight difference in resistances makes an effect in determining the CMRR?

BE CAREFUL, you need accuracy here. The calculator should have at least 4 (or 5) significant digits after the decimal point.
 - Repeat c for your measurements of resistances, V_O and CMRR.
- If you did not calculate the ice-water/hot-water/body temperature, do it now and comment on the accuracy of your results (list possible sources of error).



Experiment No. 5. Differential Amplifiers; Differential Temperature Sensor

Worksheet/Notes





Experiment No. 5. Differential Amplifiers; Differential Temperature Sensor

Worksheet/Notes

