

**The University of Jordan
School of Engineering
Electrical Engineering Department**

**EE 449
Instrumentation and Control Lab**

**EXPERIMENT 9
INSTRUMENTATION AMPLIFIER**

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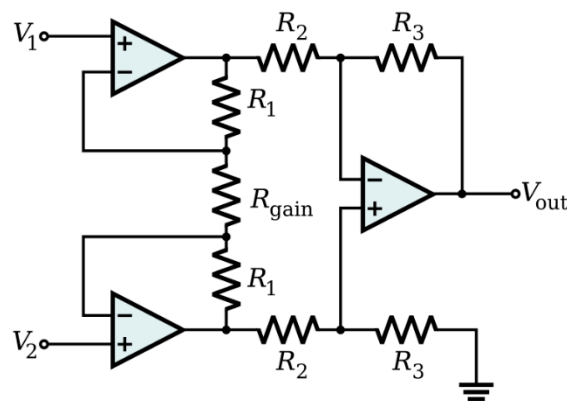
EXPERIMENT 9 INSTRUMENTATION AMPLIFIER

OBJECTIVES

1. To understand the principle of operation and advantages of instrumentation amplifiers.
2. To understand the significance of common-mode rejection ratio (CMRR).
3. To quantify the performance difference between instrumentation amplifiers and differential amplifiers.

DISCUSSION

Instrumentation amplifiers are widely used in measurements and test equipment. Typically, an instrumentation amplifier consists of three Op-Amps within one chip: one Op-Amp is used as a differential amplifier and the other two are used as input buffer amplifiers (as shown below). The input buffers provide very high input impedances, and hence, eliminate the need for input impedance matching. This is useful for performing robust measurements. Another important feature for instrumentation amplifiers is very high *common-mode rejection ratio* (CMRR).



To understand CMRR, notice that the output of the instrumentation amplifier consists of two parts, the first part is due to the input *differential* signal $(V_2 - V_1)$, and the other part is due to the input *common* signal $(V_2 + V_1)/2$, as follows,

$$V_{out} = G \times (V_2 - V_1) + G_{cm} \times \left(\frac{V_2 + V_1}{2} \right)$$

where G is the differential-mode gain, and G_{cm} is the common-mode gain. Performing proper circuit analysis, one can show that the differential-gain of the instrumentation amplifier is given by,

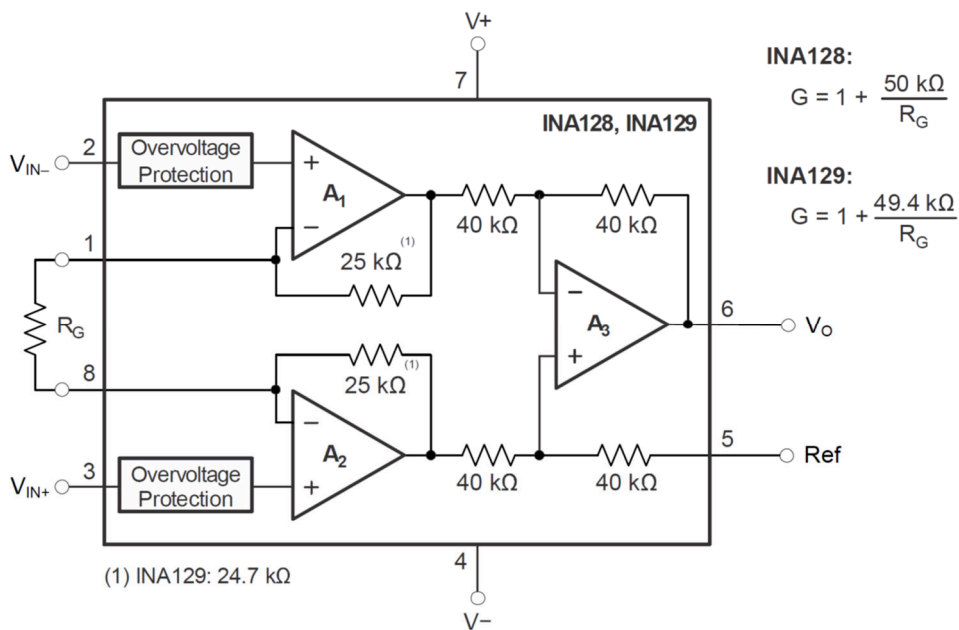
$$G = \frac{V_{out}}{V_2 - V_1} = \left(1 + \frac{2R_1}{R_{gain}} \right) \frac{R_3}{R_2}$$

This calculation requires that the pair of top and bottom resistors R_1, R_2 and R_3 are equal in value. The common-mode gain, G_{cm} , on the other hand, can be reduced to almost zero if we can reduce the mismatch in R_3/R_2 ratio. That is why instrumentation amplifier ICs typically contain laser-trimmed resistors so their values are closely matched.

The single resistor R_{gain} is used to set the desired differential-mode gain, G , for the differential input ($V_2 - V_1$) (as given by the above formula), while leaving the common-mode gain very small. In other words, if there is an identical signal that shows up on both inputs V_1 and V_2 , it is amplified with a much smaller gain compared to the difference signal $V_2 - V_1$. This ratio of both gains is called the common-mode rejection ratio (CMRR) of the amplifier, and is defined (in units of dB) as,

$$CMRR = 20 \log_{10} \left(\frac{G}{|G_{cm}|} \right)$$

The figure below shows a popular instrumentation amplifier IC, which is the INA128P. The INA128P can achieve a CMRR of 120 dB, which is a ratio of one million between the differential-mode gain and the common-mode gain.



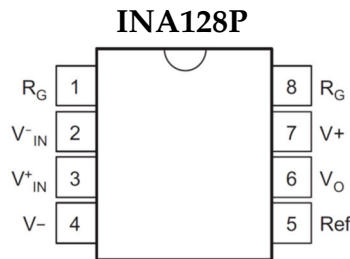
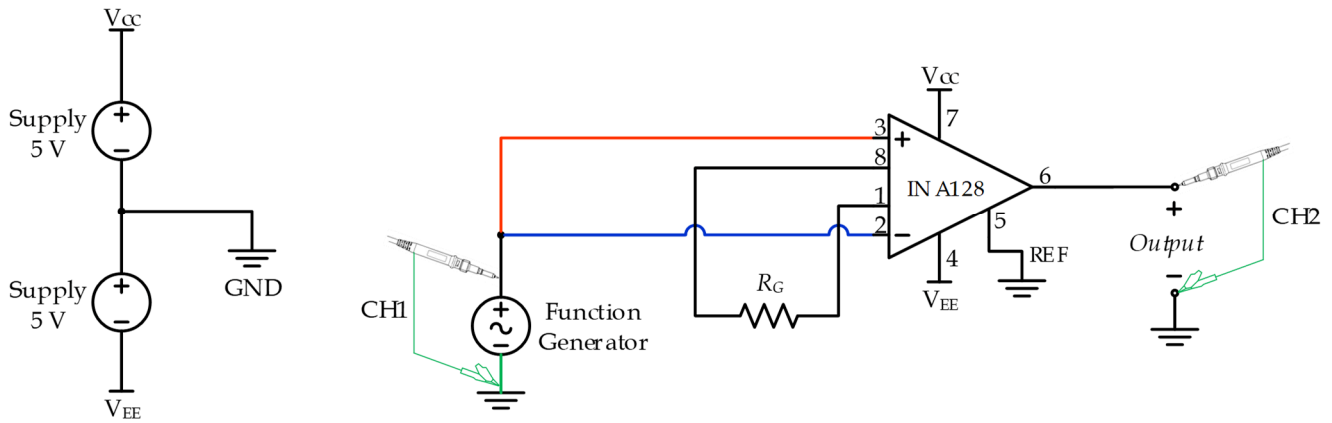
For INA128P, the differential gain is given by,

$$G = \frac{V_{out}}{V_2 - V_1} = \left(1 + \frac{2R_1}{R_{gain}} \right) \frac{R_3}{R_2} = \left(1 + \frac{2 \times 25 \text{ k}\Omega}{R_G} \right) \frac{40 \text{ k}\Omega}{40 \text{ k}\Omega} = \left(1 + \frac{50 \text{ k}\Omega}{R_G} \right)$$

Instrumentation amplifiers are used in many industrial applications to measure weak sensor data in high-noise environments, such as when reading a small thermocouple voltage from noisy industrial equipment, or when reading voltages from pressure and strain sensors, etc. Another application is when reading biological signals to conduct medical tests, such as in ECG (Electrocardiogram) to measure electrical activity of the heart, EEG (Electroencephalogram) to record electrical brain activity, and EMG (Electromyogram) to measure electrical muscle activity. In such tests, the instrumentation amplifier allows measuring very small electrical signals emitted by the human body, often in the millivolt region, that is buried in noise. This is because the human body (as well as the long measuring leads from the body to the measuring device) can act as an antenna picking up various electromagnetic interference signals, especially the 50/60 Hz noise from electrical power lines. This interference can be large and, if amplified further by the large-gain amplifier, can obscure the desired biological signal, making it difficult to see and identify.

PROCEDURE A: INSTRUMENTATION AMPLIFIER

1. Build the circuit shown below on a breadboard. The instrumentation amplifier used is the INA128P. The pin diagram for this IC is provided below. Initially, start by using a gain resistor of $R_G = 4.7 \text{ k}\Omega$.



2. Set the provided DC power supplies so that each supply generates 5 Volts, then connect them in series to obtain the +5V and -5V rails used by the instrumentation amplifier. The midpoint between the two DC supplies is your common point (Ground). Also make sure to set the current limit of the supplies to a minimum, so you do not burn the instrumentation amplifier in case you make a bad connection.

3. Using a voltmeter, measure both V_{CC} and V_{EE} compared to GND. Write both values below:

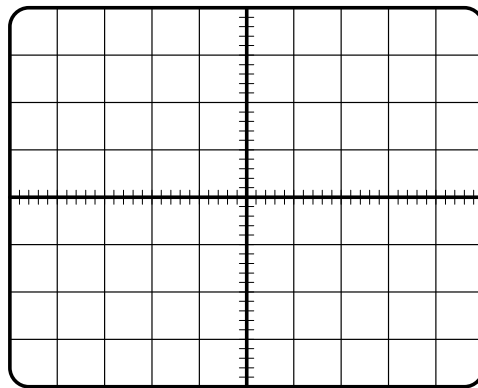
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4. Ensure that the **positive terminal** of the output of the **function generator** is connected to both inputs of the instrumentation amplifier (pins 2 and 3), thus acting as a common-mode noise signal.

5. Use CH1 of the oscilloscope to display the signal from the function generator, while simultaneously using CH2 to display the output signal from the instrumentation amplifier. Set CH1 vertical scale to **2 V/DIV** and use **DC coupling**. Set CH2 vertical scale to **10 mV/DIV** and use **DC coupling**. Set trigger type to **Edge**, and trigger source to **CH1**. Set the horizontal time scale to **1 ms/DIV**. Since we are dealing with very small signals, **avoid** using the Auto SET feature of the oscilloscope.
6. Set the function generator to produce a **1 kHz, 10Vpp sinusoidal** waveform at the output terminal without any DC offset.
7. Observe and draw below both the input signal (CH1) and output signal (CH2) from the instrumentation amplifier. The output signal might look noisy due to its very small value.



8. Using the oscilloscope, measure the peak-to-peak value of both the input signal (CH1) and output signal (CH2), and write these values below. You might need to use the divisions on the oscilloscope screen to read the peak-to-peak values, rather than relying on the MEASURE feature of the oscilloscope due to the small and noisy output signal. Alternatively, you might try going into the **ACQUIRE** menu of the oscilloscope, and change the **Acquire Mode** from **Normal** to **Average**, and set the **Average Count** to 128, which attempts to smooth the output signal shown on the oscilloscope. Remember to go back to Normal Acquire Mode for later steps in the procedure.

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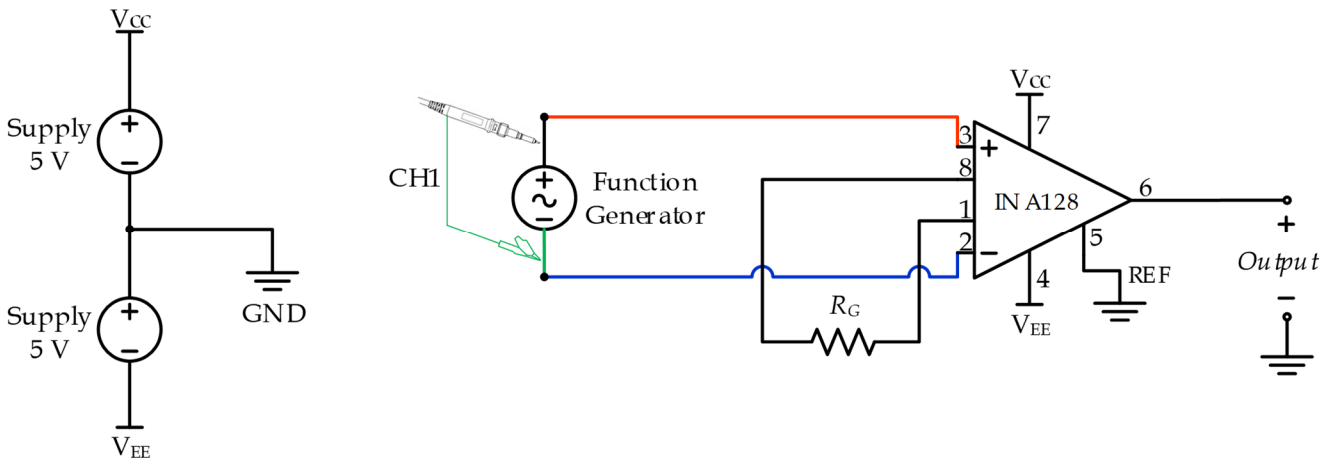
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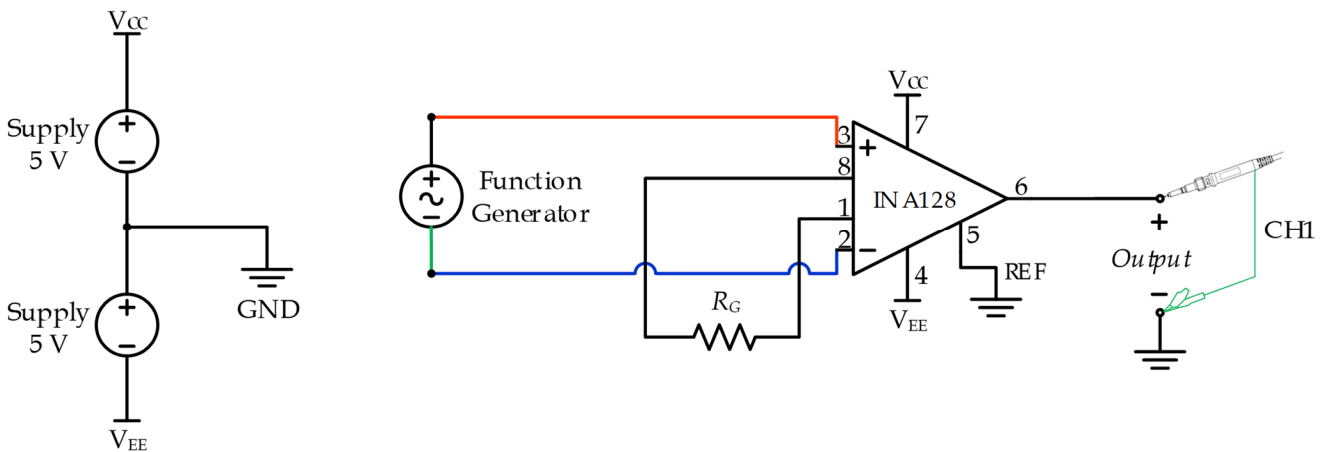
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9. Now reconfigure you circuit so that the function generator output becomes a differential input to the instrumentation amplifier as shown below. Keep the gain resistor $R_G = 4.7\text{ k}\Omega$.



10. Use CH1 of the oscilloscope to observe the output signal from the function generator. Disconnect CH2 from the circuit. Set the function generator to produce a **1 kHz, 0.5Vpp sinusoidal** waveform at the output terminal without any DC offset.

11. Now disconnect CH1 of the oscilloscope from the input of the instrumentation amplifier, and move it to the output as shown below.



12. Measure the peak-to-peak value of the output signal, and write it below.

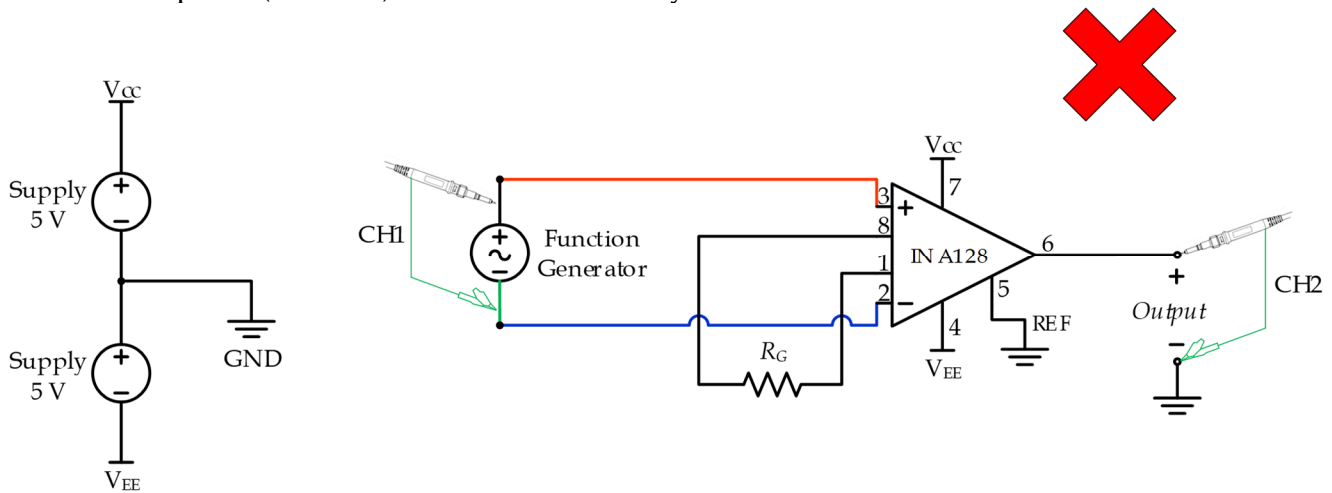
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13. Remember here that you are dealing with differential signals, so you do not want to have CH1 of the oscilloscope connected to the function generator, while CH2 of the oscilloscope is simultaneously connected to the output of the instrumentation amplifier (as shown below). This is because the negative terminals of both CH1 and CH2 are connected to each other (and the earth wire) inside the oscilloscope (i.e., they represent a short circuit). This means that you

will introduce an unintended short circuit between pin 2 of the instrumentation amplifier and the common point (Ground), which is not what you want.



14. Now that you have measured the output due to a common-mode input (step 8) and also the output due to a differential-mode input (step 12), write those values in the table below.

R_G	Frequency	V_{cm} pk-to-pk	V_{out} pk-to-pk	V_{diff} pk-to-pk	V_{out} pk-to-pk
4.7 k Ω	1 kHz	10 Vpp	_____ Vpp	0.5 Vpp	_____ Vpp
4.7 k Ω	20 kHz	5 Vpp	_____ Vpp	0.5 Vpp	_____ Vpp
4.7 k Ω	100 kHz	5 Vpp	_____ Vpp	0.5 Vpp	_____ Vpp
2.2 k Ω	1 kHz	10 Vpp	_____ Vpp	0.3 Vpp	_____ Vpp
2.2 k Ω	20 kHz	5 Vpp	_____ Vpp	0.3 Vpp	_____ Vpp
2.2 k Ω	100 kHz	5 Vpp	_____ Vpp	0.3 Vpp	_____ Vpp

15. Next, repeat the above procedure by measuring the common-mode output and also the differential-mode output versus input when changing the frequency to 20 kHz and 100 kHz, and also changing the gain resistor to $R_G = 2.2 \text{ k}\Omega$. Use your measured values to fill the above table. Also remember that varying the frequency of the function generator might change the output voltage amplitude slightly, so always verify your input signal voltage before reading the output voltage levels.

16. Use the above measured values to calculate the common mode gain, differential-mode gain, and CMRR for the different cases shown above. Write your answers in the table below.

R_G	Frequency	G_{cm} (unitless)	G_{diff} (unitless)	CMRR (unitless)	CMRR (dB)
4.7 k Ω	1 kHz				
4.7 k Ω	20 kHz				
4.7 k Ω	100 kHz				
2.2 k Ω	1 kHz				
2.2 k Ω	20 kHz				
2.2 k Ω	100 kHz				

17. Explain your findings with regard to the difference between the common-mode gain and the differential-mode gain.

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18. Explain the effect of input signal frequency and instrumentation amplifier gain on CMRR.

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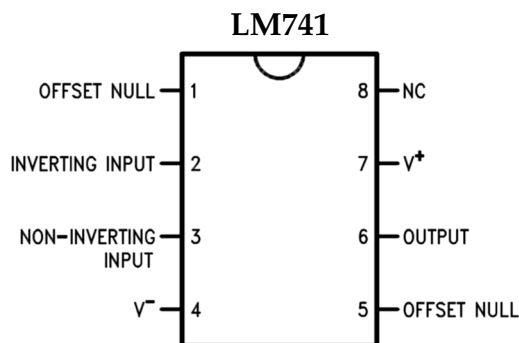
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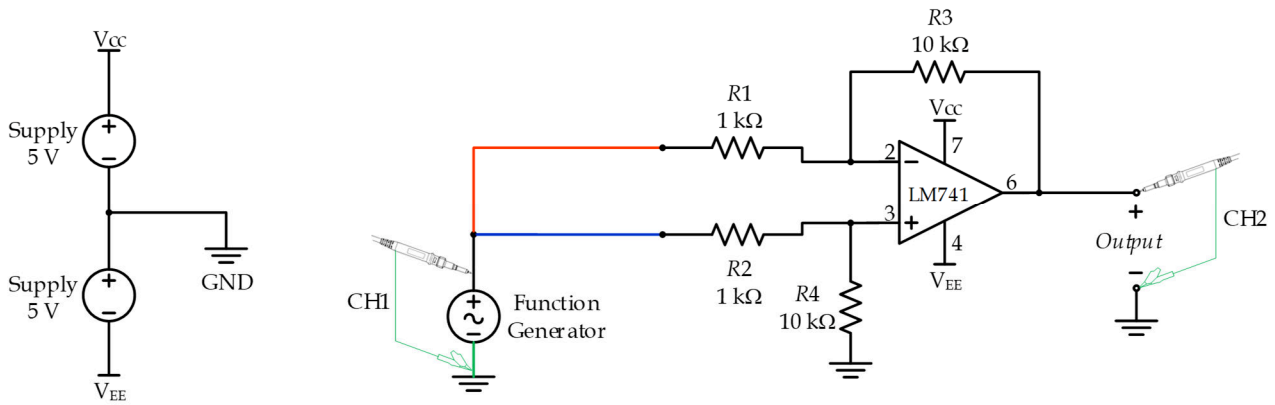
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PROCEDURE B: DIFFERENTIAL AMPLIFIER

1. Build the differential amplifier circuit shown in the next page. Use an LM741 single Op-Amp IC, the pin diagram of which is shown below. Remember that the gain of this differential amplifier is $G = R_3/R_1 = 10$.

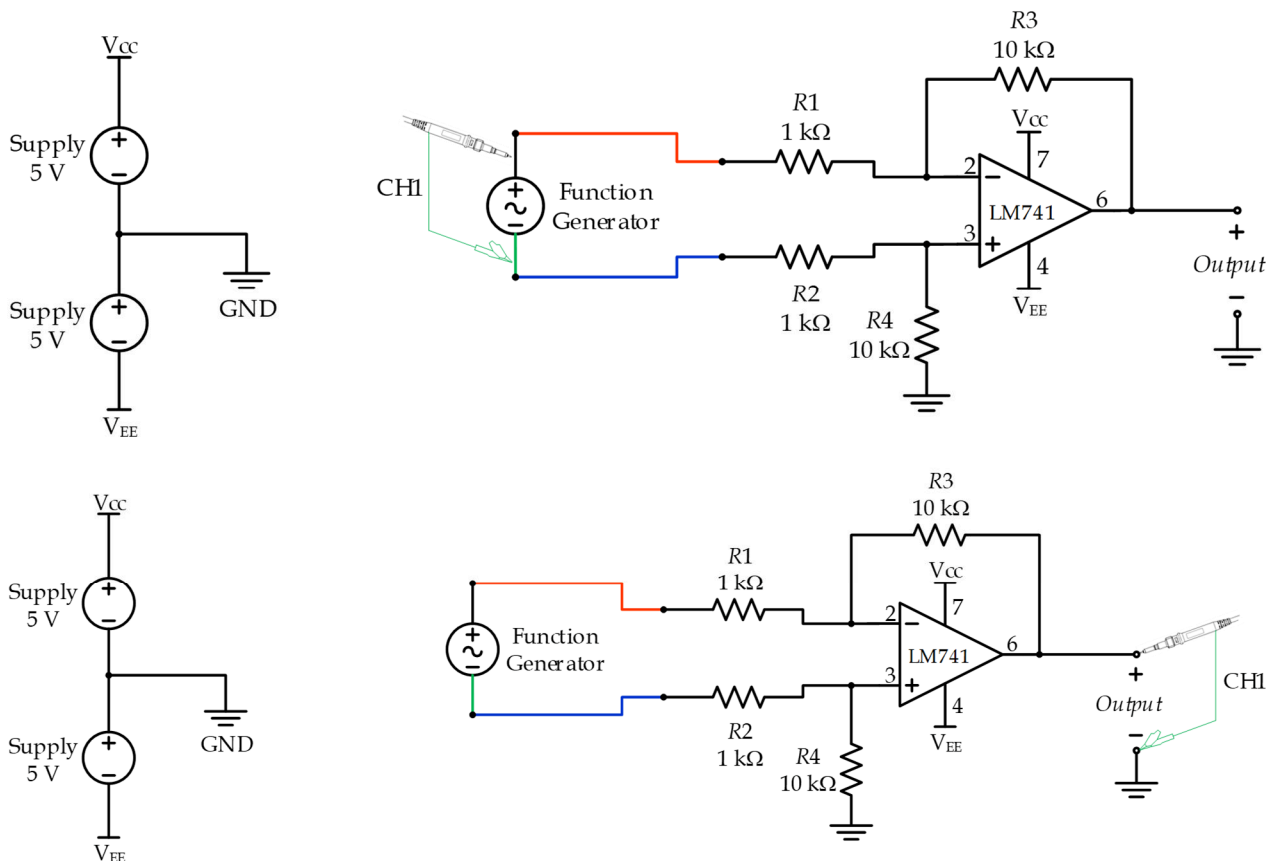




2. Repeat the procedure you executed for the instrumentation amplifier but this time to measure the output of this differential amplifier in response to a common-mode input signal of: (10 Vpp, 1 kHz), (5 Vpp, 20 kHz) and (5 Vpp, 100 kHz). Use the above circuit. Write you measured values in the table below.

Gain	Frequency	V_{cm} pk-to-pk	V_{out} pk-to-pk	V_{diff} pk-to-pk	V_{out} pk-to-pk
10	1 kHz	10 Vpp	___ Vpp	0.5 Vpp	___ Vpp
10	20 kHz	5 Vpp	___ Vpp	0.5 Vpp	___ Vpp
10	100 kHz	5 Vpp	___ Vpp	0.5 Vpp	___ Vpp

3. Repeat the procedure you executed for the instrumentation amplifier but this time to measure the output of the differential amplifier in response to a differential-mode input signal of 0.5 Vpp and 1 kHz, 20 kHz and 100 kHz frequencies. Use the circuit shown below to perform your measurements. Write the results in the above table.



4. Use the above measured values to calculate the common mode gain, differential-mode gain, and CMRR for the different cases shown above. Write your answers in the table below.

Gain	Frequency	G_{cm} (unitless)	G_{diff} (unitless)	CMRR (unitless)	CMRR (dB)
10	1 kHz				
10	20 kHz				
10	100 kHz				

5. Explain your findings with regards to the difference between the CMRR for an instrumentation amplifier versus a regular differential amplifier. Explain why this is the case.

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