Experiment 03: Study of Operational Amplifiers

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(Subgroup - A7)

1 Aim

- Study of op-Amp as inverting and non-inverting amplifiers.
- Study the application of op-Amp as adder and subtractor.

2 Theory

An operational amplifier is a differential amplifier, which takes two voltage inputs and amplifies the difference between them. An ideal op-Amp has infinite input impedance, zero output impedance and large open loop voltage gain $\mathcal{A}_v^{(o)}$. For the open loop, if v_+ and v_- are the voltages at the two input terminals of the op-Amp, we have the output voltage as:

$$v_{\text{out}} = \mathcal{A}_v^{(o)}(v_+ - v_-)$$

The output of an op-Amp cannot be arbitrarily high and is limited by the power supply. After a certain point, the output saturates. Op-Amp is very useful in performing mathematical calculations like arithmetic operations, differentiation, integration, etc.

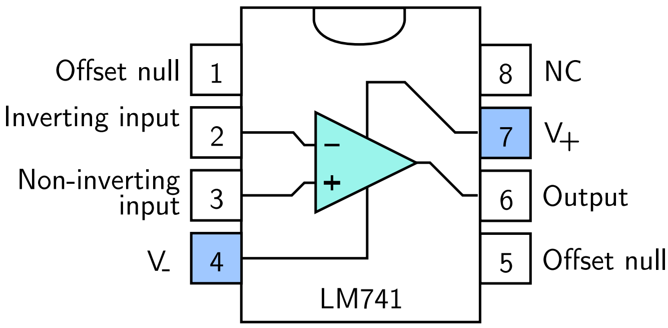

Figure 1: LM741 IC as an op-Amp, showing the pin configurations

The op-Amp used in this experiment is the LM741, which is an 8 pin IC. The pin configuration of the LM741 is shown above.

V_+ and V_- denote the supply voltage to the op-Amp. Offset Null refers to a calibration feature in the op-Amp that allows adjusting the output voltage to zero when the input is zero, compensating for internal voltage discrepancies. The NC stands for Not Connected Terminal which is used as a filler space, so that the number of pins become even and it becomes easier to place the IC on the breadboard.

op-Amp as Inverting Amplifier:

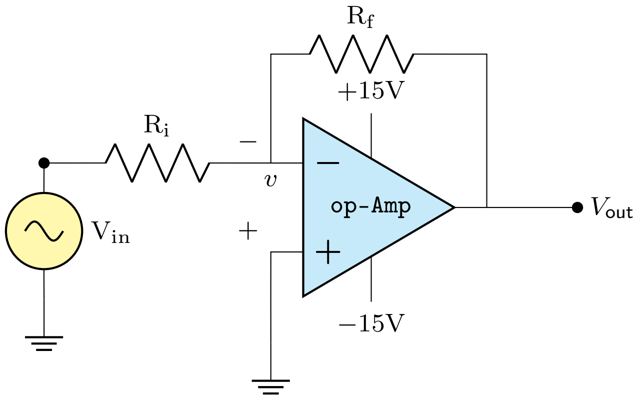

Figure 2: Circuit diagram for an inverting op-Amp

Since current through op-Amp due to high resistance is almost negligible, from Kirchoff current law at the junction, we get:

$$\frac{V_{in} - v}{R_i} = \frac{v - V_{out}}{R_f}$$

From virtual ground condition, $v \approx 0$ Hence we obtain an expression for the gain $\mathcal{A}$ as:

$$V_{out} = -\left(\frac{R_f}{R_i}\right) V_{in} \implies \boxed{\mathcal{A} = \frac{V_{out}}{V_{in}} = -\left(\frac{R_f}{R_i}\right)}$$

op-Amp as Non-Inverting Amplifier:

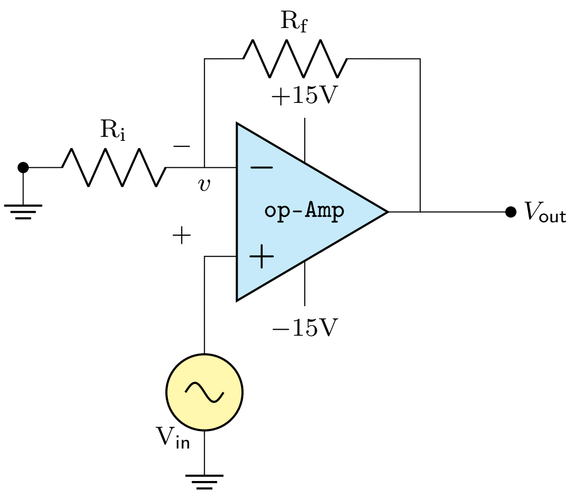

Figure 3: Circuit diagram for an non-inverting op-Amp

Since current through op-Amp due to high resistance is almost negligible, from Kirchoff current law at the junction, we get:

$$\frac{-v}{R_i} = \frac{v - V_{out}}{R_f} \implies V_{out} = v\left(1 + \frac{R_f}{R_i}\right)$$

From virtual ground condition, $v \approx V_{in}$, hence we get an expression for the gain $\mathcal{A}$ as:

$$V_{out} = V_{in}\left(1 + \frac{R_f}{R_i}\right) \implies \boxed{\mathcal{A} = \frac{V_{out}}{V_{in}} = 1 + \frac{R_f}{R_i}}$$

op-Amp as Adder:

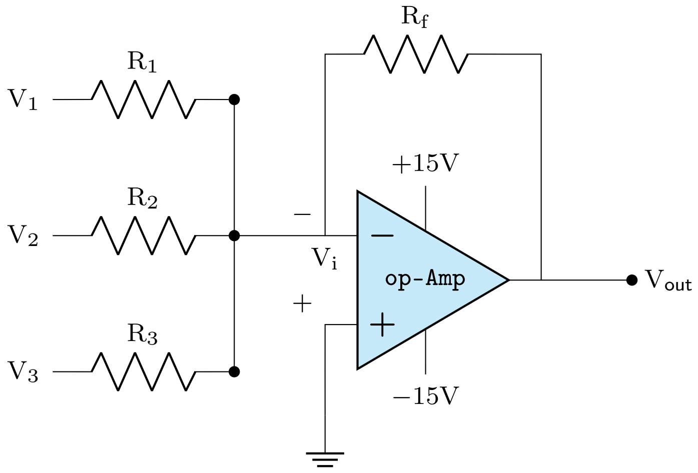

Figure 4: Circuit for op-Amp as an adder

For the circuit shown above, the current through op-Amp is negligible, hence the total current through the three resistors R_1, R_2, R_3 goes through R_f. Applying Kirchoff's current law at the junction, we get:

$$\frac{V_{out} - V_i}{R_f} = \frac{V_i - V_1}{R_1} + \frac{V_i - V_2}{R_2} + \frac{V_i - V_3}{R_3}$$

From the virtual ground condition, $V_i \approx 0$, hence:

$$V_{out} = -R_f \left(\frac{V_1}{R_1} + \frac{V_2}{R_2} + \frac{V_3}{R_3} \right)$$

If we take $R_f = R_1 = R_2 = R_3$, then:

$$\boxed{V_{out} = -(V_1 + V_2 + V_3)}$$

Hence, the circuit acts as an adder, that is, it adds the individual input voltages.

op-Amp as Subtractor:

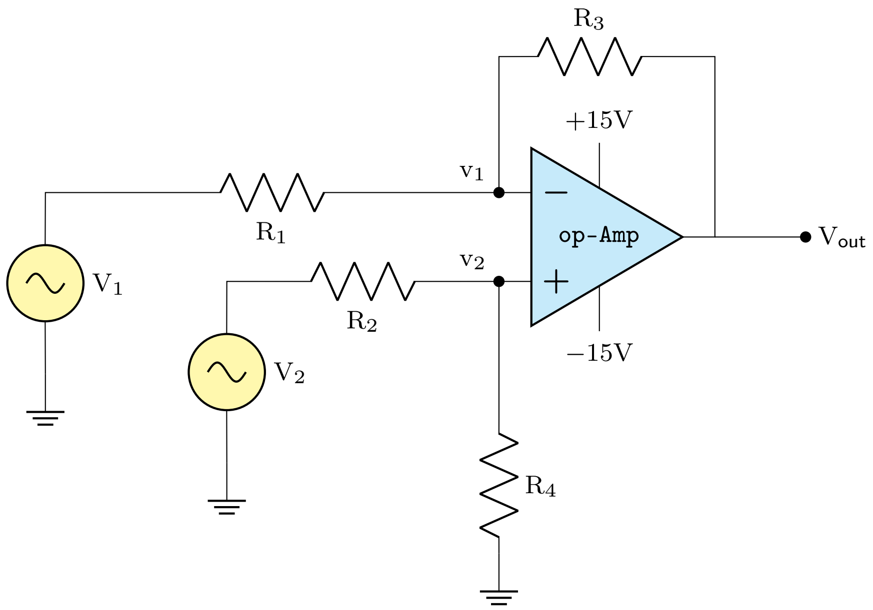

Figure 5: Circuit diagram for op-Amp as a subtractor

For the circuit shown above, the current through op-Amp is negligible. Thus, using Kirchoff's current law at the junctions, we get:

$$\frac{V_1 - v_1}{R_1} = \frac{v_1 - V_{out}}{R_3} = \frac{V_1 - V_{out}}{R_1 + R_3} \implies v_1 = \frac{R_3}{R_1 + R_3}(V_1 - V_{out}) + V_{out}$$

$$\frac{V_2 - v_2}{R_2} = \frac{v_2 - 0}{R_4} = \frac{V_2}{R_2 + R_4} \implies v_2 = \frac{R_4}{R_2 + R_4}V_2$$

From the virtual ground condition, $v_1 \approx v_2$, hence:

$$\frac{R_3}{R_1 + R_3}V_1 + \frac{R_1}{R_1 + R_3}V_{out} = \frac{R_4}{R_2 + R_4}V_2 \implies V_{out} = \frac{R_4(R_1 + R_3)}{(R_4 + R_2)R_1}V_2 - \frac{R_3}{R_1}V_1$$

If we take $R_1 = R_2 = R_3 = R_4$, then:

$$\boxed{V_{out} = (V_2 - V_1)}$$

Hence, the circuit acts as a subtractor, that is, it subtracts the individual input voltages.

3 Data and Calculation

In the first part, we studied the op-Amp as an inverting amplifier and obtained the gained by changing different values of the input and the feedback resistances. We then compared the average gain obtained to the theoretical value obtained from the ratio of the resistances.

$R_i = 1\,k\Omega$, $R_f = 2.2\,k\Omega$			$R_i = 1\,k\Omega$, $R_f = 10\,k\Omega$			$R_i = 10\,k\Omega$, $R_f = 22\,k\Omega$			$R_i = 2.2\,k\Omega$, $R_f = 10\,k\Omega$		
V_{in} (V)	V_{out} (V)	Gain	V_{in} (V)	V_{out} (V)	Gain	V_{in} (V)	V_{out} (V)	Gain	V_{in} (V)	V_{out} (V)	Gain
0.0	0.02	—	0.0	0.12	—	0.0	0.02	—	0.0	0.05	—
0.5	1.22	2.44	0.2	2.26	11.3	0.5	1.32	2.64	0.2	1.07	5.35
1.0	2.35	2.35	0.4	4.56	11.4	1.0	2.38	2.38	0.4	2.24	5.6
1.5	3.39	2.26	0.6	6.91	11.5	1.5	3.53	2.35	0.6	2.92	4.87
2.0	4.56	2.28	0.8	8.91	11.1	2.0	4.54	2.27	0.8	3.99	4.99
2.5	5.64	2.26	1.0	10.52	10.5	2.5	5.67	2.27	1.0	4.70	4.70
3.0	6.77	2.26	1.2	12.67	10.6	3.0	6.89	2.30	1.2	5.90	4.92
3.5	7.85	2.24	1.4	13.20	9.43	3.5	7.90	2.26	1.4	6.76	4.83
4.0	8.97	2.24				4.0	9.00	2.25	1.6	7.46	4.66
4.5	10.02	2.23				4.5	10.13	2.25	1.8	8.61	4.78
5.0	11.09	2.22				5.0	11.22	2.24	2.0	9.45	4.73
						5.5	12.52	2.28	2.2	10.47	4.76
						6.0	13.25	2.21	2.4	11.21	4.67
									2.6	12.37	4.76
									2.8	13.07	4.67
									3.0	13.21	4.40
Avg Gain: 2.28 $\frac{R_f}{R_i} = 2.2$			**Avg Gain: 10.84** $\frac{R_f}{R_i} = 10.0$			**Avg Gain: 2.31** $\frac{R_f}{R_i} = 2.2$			**Avg Gain: 4.85** $\frac{R_f}{R_i} = 4.54$		

Table 1: Experimental data for different R_i and R_f values with average gains for op-Amp as an inverting amplifier.

In the second part, we studied the op-Amp as an non-inverting amplifier and obtained the gained by changing different values of the input and the feedback resistances. We then compared the average gain obtained to the theoretical value obtained from the ratio of the resistances.

$R_i = 2.2\,k\Omega$, $R_f = 10\,k\Omega$			$R_i = 1\,k\Omega$, $R_f = 2.2\,k\Omega$			$R_i = 10\,k\Omega$, $R_f = 22\,k\Omega$		
V_{in} (V)	V_{out} (V)	Gain	V_{in} (V)	V_{out} (V)	Gain	V_{in} (V)	V_{out} (V)	Gain
0.0	0.07	–	0.0	0.05	–	0.0	0.05	–
0.2	1.74	8.70	0.5	1.91	3.82	0.5	1.84	3.68
0.4	2.60	6.50	1.0	3.31	3.31	1.0	3.55	3.55
0.6	3.51	5.85	1.5	4.92	3.28	1.5	5.15	3.43
0.8	4.75	5.94	2.0	6.57	3.29	2.0	6.76	3.38
1.0	5.71	5.71	2.5	8.24	3.30	2.5	8.39	3.36
1.2	6.93	5.78	3.0	9.73	3.24	3.0	10.07	3.36
1.4	7.96	5.69	3.5	11.51	3.29	3.5	11.55	3.30
1.6	9.07	5.67	4.0	12.93	3.23	4.0	13.06	3.27
1.8	10.46	5.81	4.5	14.20	3.16	4.5	14.36	3.19
2.0	11.68	5.84						
2.2	12.68	5.76						
2.4	13.85	5.77						
2.6	14.31	5.50						
Avg Gain: 5.76 (removing first two anomalous values) $1 + \frac{R_f}{R_i} = 5.54$			**Avg Gain: 3.32** $1 + \frac{R_f}{R_i} = 3.2$			**Avg Gain: 3.39** $1 + \frac{R_f}{R_i} = 3.2$		

Table 2: Experimental data for different R_i and R_f values with average gains for op-Amp as a non-inverting amplifier.

In the third part, we studied the op-Amp as an adder. From the main voltage from the power supply, we took two branches in parallel and used different resistances across each branch to obtain three different input voltages which we used as input to the op-Amp and calculated the corresponding output voltage.

V_1 (V)	V_2 (V)	V_3 (V)	V_{out}(V) (measured)	$V_1 + V_2 + V_3$ (V)
0.0	0.00	0.01	0.02	0.01
1.0	1.06	1.07	3.18	3.13
1.0	0.68	1.08	2.79	2.76
1.5	1.01	1.28	3.83	3.79
1.5	0.85	0.85	3.25	3.2
2.0	1.12	1.33	4.47	4.45
2.0	2.09	1.12	5.22	5.21
2.5	1.52	1.66	5.66	5.68
3.1	1.72	2.57	7.33	7.39
3.1	2.68	2.57	8.28	8.35
3.5	2.91	2.91	9.21	9.32
4.0	2.96	3.22	9.96	10.18
4.5	3.36	2.37	10.01	10.23
4.5	4.35	2.9	11.44	11.75
5.0	2.55	2.53	9.88	10.08

Table 3: Data Table for op-Amp as an adder

From the measured output voltage and actual value of the addition between input voltages, we can see that both the values are very close to each other. Thus, we showed the op-Amp as a adder.

In the fourth part, we studied the op-Amp as a subtractor. From the main voltage from the power supply, we took another branch in parallel and used different resistance across this branch to obtain another input voltage which we used as input to the op-Amp and calculated the corresponding output voltage.

V_1 (V)	V_2 (V)	V_{out}(V) (measured)	$V_2 \sim V_1$ (V)
1.0	0.79	0.29	0.21
2.0	1.45	0.54	0.55
2.5	2.52	0.06	0.02
2.5	1.82	0.65	0.68
4.3	2.91	1.39	1.39
5.0	3.37	1.60	1.63
5.5	4.29	1.15	1.21
6.0	4.32	1.58	1.68
6.5	4.38	2.02	2.12
7.0	4.64	2.21	2.36
7.5	5.23	2.06	2.27
8.0	5.52	2.18	2.48
8.5	6.62	1.54	1.88
9.0	7.32	1.48	1.68
9.5	7.67	1.56	1.83
10.0	8.19	1.64	1.81

Table 4: Data Table for op-Amp as a subtractor

From the measured output voltage and actual value of the different between input voltages, we can see that both the values are very close to each other. Thus, we showed the op-Amp as a subtractor.

4 Sources of Error

- Different multimeters (with different resistances) were used to measure the voltages and hence, the adder and subtractor readings deviated from the theoretical values expected from addition and subtraction since different resistances had different effect on the voltage reading.
- There could be some error in the measurement of the resistances and the voltage readings due to internal resistance of the multimeter. Thus, the gains could have been slightly different from the theoretical values.

5 Discussion and Conclusion

Using LM741 IC, we studied the properties of op-Amp as an inverting and non-inverting amplifier and calculated the corresponding gain. Then to demonstrate the use of op-Amp in performing mathematical calculations, we used it as an adder and subtractor and verified that the obtained output voltage was very close to the expected theoretical value.