Experiment 03: Study of Operational Amplifiers

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1 Aim

- Study of op-Amp as inverting and non-inverting amplifiers.
- Study of 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.

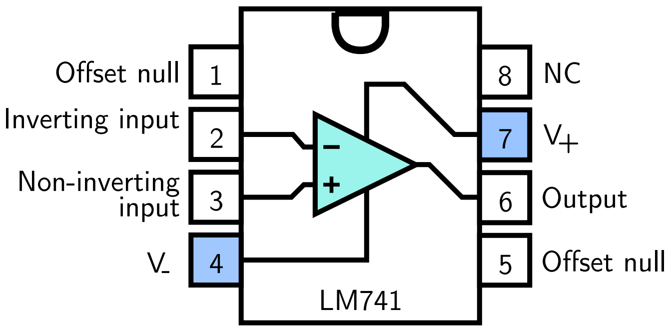

Figure 1: Real 8 pin op-Amp showing the pin configurations

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.

op-Amp as Inverting Amplifier:

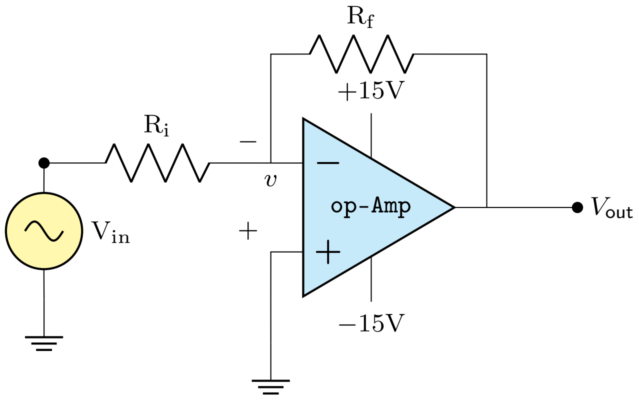

Figure 2: Circuit diagram for an inverting op-Amp

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

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

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

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

op-Amp as Non-Inverting Amplifier:

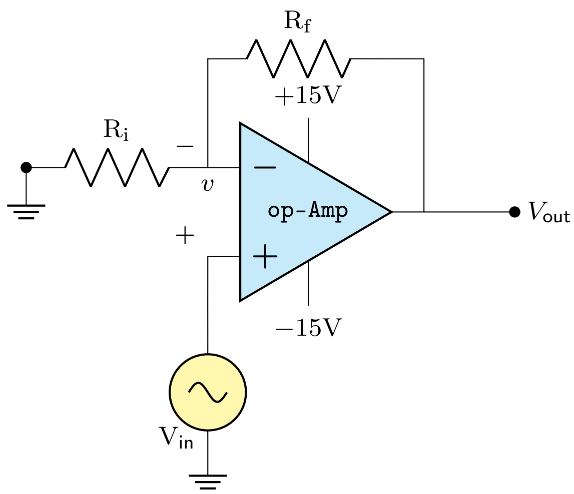

Figure 3: Circuit diagram for an non-inverting op-Amp

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

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

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

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

op-Amp as Adder:

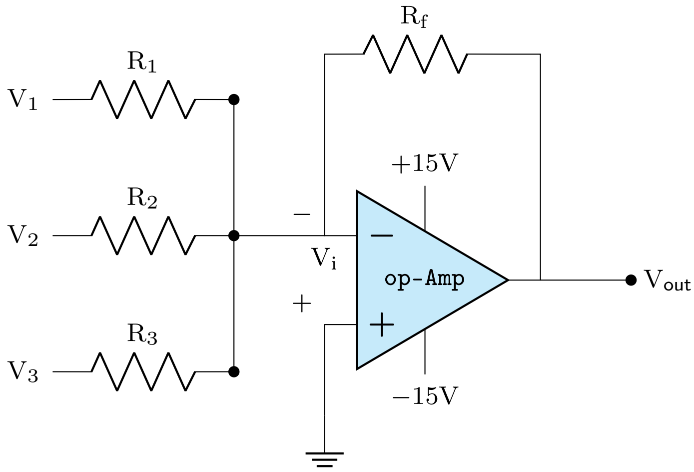

Figure 4: Circuit for op-Amp as an adder

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

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

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

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

If we take $\mathrm{R_f} = \mathrm{R_1} = \mathrm{R_2} = \mathrm{R_3}$, then:

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

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

op-Amp as Subtractor:

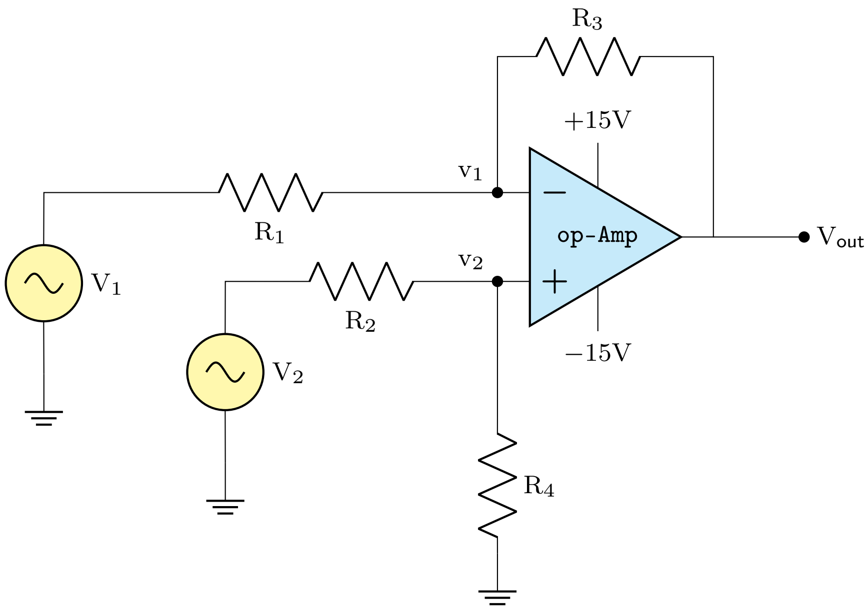

Figure 5: Circuit diagram for op-Amp as a subtractor

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:

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

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

$R_i = 1\,k\Omega$, $R_f = 2.2\,k\Omega$			$R_i = 1\,k\Omega$, $R_f = 10\,k\Omega$			$R_i = 10\,k\Omega$, $R_f = 22\,k\Omega$			$R_i = 2.2\,k\Omega$, $R_f = 10\,k\Omega$		
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.

$R_i = 2.2\,k\Omega$, $R_f = 10\,k\Omega$			$R_i = 1\,k\Omega$, $R_f = 2.2\,k\Omega$			$R_i = 10\,k\Omega$, $R_f = 22\,k\Omega$		
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.

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.

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

5 Discussion and Conclusion