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.

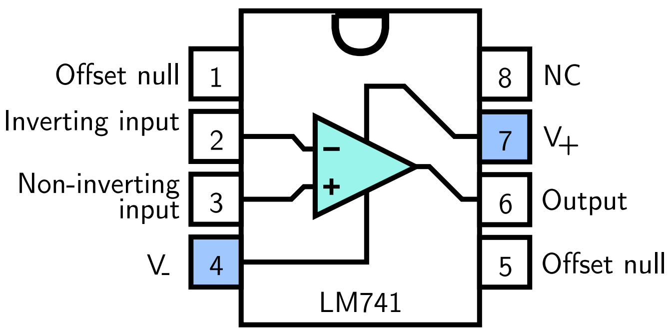

Figure 1: Real 8 pin op-Amp showing the pin configurations

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:

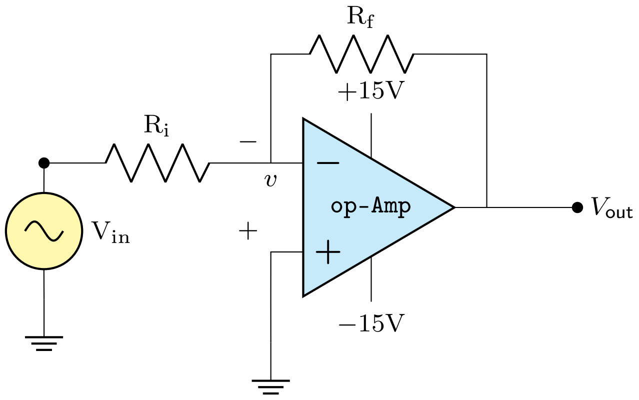

Figure 2: Circuit diagram for an inverting op-Amp

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:

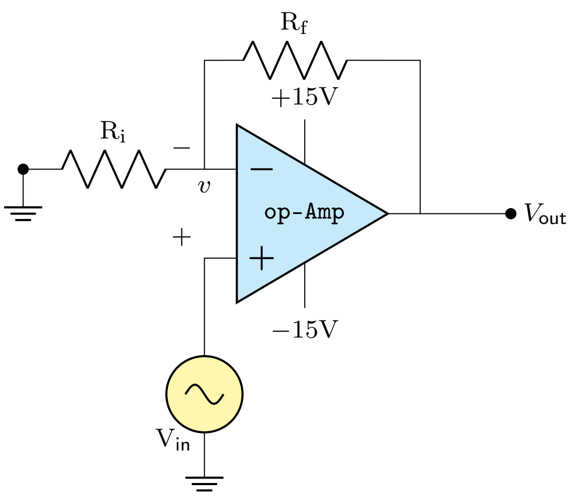

Figure 3: Circuit diagram for an non-inverting op-Amp

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:

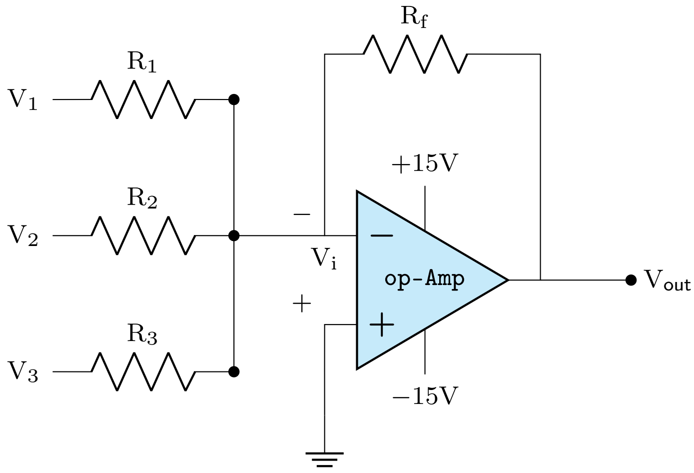

Figure 4: Circuit for op-Amp as an adder

For the circuit shown above, the current through op-Amp is negligible, hence the total current through the three resistors 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:

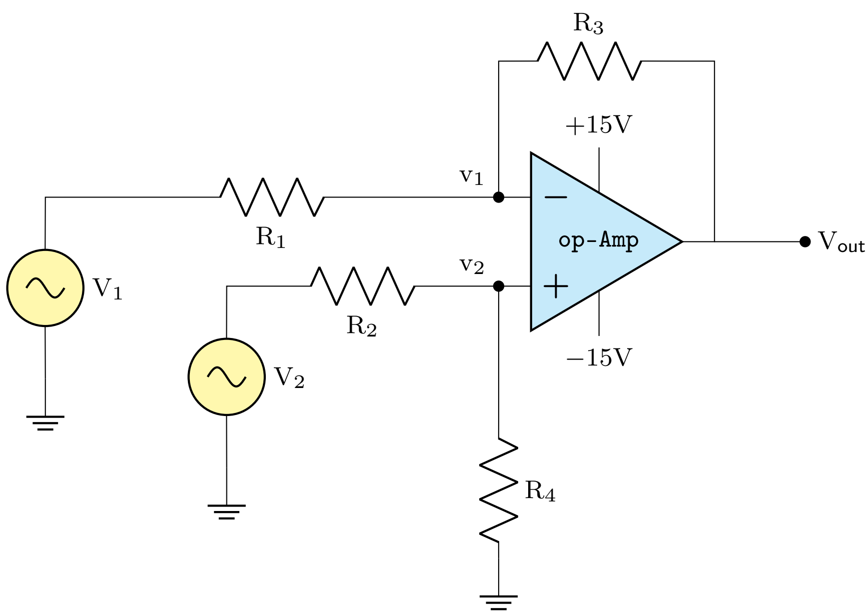

Figure 5: Circuit diagram for op-Amp as a subtractor

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:

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

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

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

4 Sources of Error

5 Discussion and Conclusion