Experiment Report:
Differentiation and Integration using OPAMP and active low pass filter

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Abstract

Operational Amplifier (OPAMP) circuits were configured to perform differentiation, integration, and active filtering. In the differentiator and integrator configurations, appropriate combinations of resistors and capacitors were used in the input and feedback paths to obtain output waveforms corresponding to the time derivative and integral of the input signal, respectively. The observed output waveforms for sine, triangular, and square inputs were consistent with the theoretical expectations. Further, an active low-pass filter circuit was built using the OPAMP, and its frequency response was obtained experimentally. The cutoff frequency measured from the data closely matched the theoretically calculated value. The experiment successfully demonstrated the ability of OPAMP-based circuits to perform differentiation and integration and its use as an active low-pass filter.

1 Objectives

- To demonstrate the use of OPAMP as a differentiator.
- To demonstrate the use of OPAMP as an integrator.
- Building an active low-pass filter and obtaining its cutoff frequency.

2 Theory and Working Formula

Operational amplifiers (OPAMPs) are high-gain voltage amplifiers with differential input and single-ended output. By selecting suitable resistor and capacitor combinations in the feedback and input networks, OPAMPs can be configured to perform mathematical operations such as integration and differentiation, as well as filtering of signals in specific frequency ranges.

In this experiment, three OPAMP-based circuits are studied: the integrator, the differentiator, and the active low-pass filter. Each circuit demonstrates a distinct frequency-dependent behavior, governed by the arrangement of the reactive (capacitive) and resistive components in the feedback loop.

2.1 Differentiator

An OPAMP integrator circuit is obtained by placing a resistor R at the input and a capacitor C in the feedback path, as shown in figure 1a. A resistor is added in parallel to the capacitor in the feedback to stabilise the circuit. Assuming ideal OPAMP behavior:

$$i = C_{\text{in}} \frac{dV_{\text{in}}}{dt} = \frac{-V_{\text{out}}}{R_f} \tag{1}$$

Hence, the output voltage is:

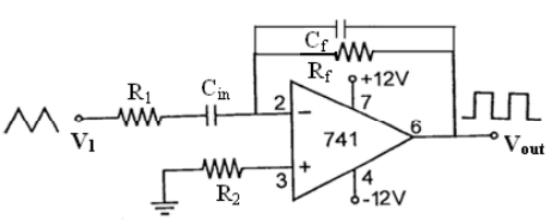
$$V_{\text{out}}(t) = -R_f C_{\text{in}} \frac{dV_{\text{in}}(t)}{dt} \tag{2}$$

The output is therefore proportional to the time derivative of the input voltage, with a 180° phase inversion. For a sinusoidal input, the magnitude of voltage gain increases linearly with frequency:

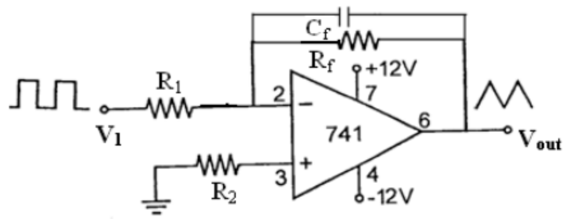
$$|A_v| = \omega R_f C_{\text{in}} \tag{3}$$

2.2 Integrator

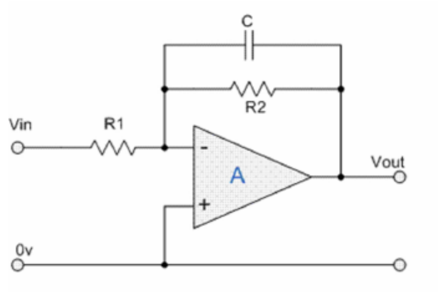
An OPAMP integrator circuit is obtained by placing a resistor R at the input and a capacitor C in the feedback path, as shown in figure 1b. A resistor is added in parallel to the capacitor in the feedback to stabilise the



(a) Differentiator circuit



(b) Integrator circuit



(c) Active low-pass filter circuit

Figure 1: Circuit diagrams

circuit. For an ideal OPAMP, the input current through R equals the current through C. Hence,

$$i = \frac{V_{\text{in}}}{R_1} = -C_f \frac{dV_{\text{out}}}{dt} \tag{4}$$

Integrating both sides with respect to time gives:

$$V_{\text{out}}(t) = -\frac{1}{R_1 C_f} \int V_{\text{in}}(t)\, dt + V_{\text{out}}(0) \tag{5}$$

Thus, the output voltage is proportional to the time integral of the input voltage, with a phase inversion of 180°. The magnitude of voltage gain decreases with frequency and is given by:

$$|A_v| = \frac{1}{\omega R_1 C_f} \tag{6}$$

2.3 Active Low-Pass Filter

As seen in equation 6, the gain of the integrator circuit decreases with an increase in frequency. So the integrator circuit acts as an active low-pass filter. The circuit diagram for the active low-pass filter is given in figure 1c.

The transfer function of a first-order low-pass filter is given by:

$$A_v(\omega) = \frac{A_0}{\sqrt{1 + (\omega/\omega_c)^2}} \tag{7}$$

where $\omega_c = 1/(RC)$ is the cutoff angular frequency and A_0 is the passband gain, determined by the feedback resistors as:

$$A_0 = 1 + \frac{R_f}{R_i} \tag{8}$$

At frequencies $\omega \ll \omega_c$, the amplifier behaves normally with gain A_0, whereas for $\omega \gg \omega_c$, the output decreases at a rate of -20 dB/decade.

3 Materials Required

(i) OPAMP IC 741, (ii) D.C. power supply, (iii) Resistors, (iv) Digital multimeter, (v) Connecting wires, (vi) Breadboard, (vii) Function generator, (viii) Digital storage oscilloscope.

4 Observations

4.1 OPAMP differentiator circuit

Table 1: The input and output waveforms observed for the OPAMP differentiator circuit

Input waveform	Sine	Triangular	Square
Output waveform	Sine	Square	Spikes

(a) Input: Sine
Output: Sine

(b) Input: Triangular
Output: Square

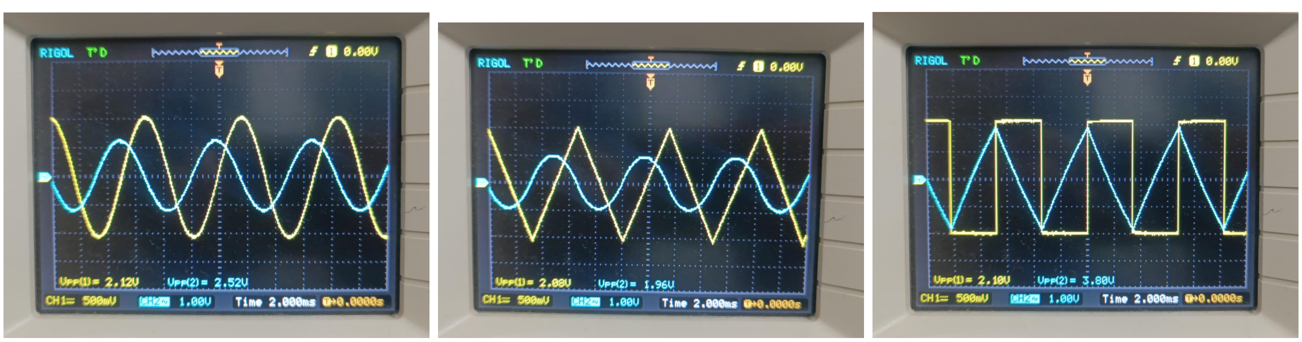
(c) Input: Square
Output: Spikes

Figure 2: The input and output waveforms observed for the OPAMP differentiator circuit.

4.2 OPAMP integrator circuit

Table 2: The input and output waveforms observed for the OPAMP integrator circuit

Input waveform	Sine	Triangular	Square
Output waveform	Sine	Quadratic Function	Triagular



(a) Input: Sine
Output: Sine

(b) Input: Triangular
Output: Quadratic Function

(c) Input: Square
Output: Triangular

Figure 3: The input and output waveforms observed for the OPAMP integrator circuit.

4.3 Active Low-pass filter

$R_1 = 9.92\text{k}\Omega$, $R_f = 100.9\text{k}\Omega$, $C_f = 11.29\text{nF}$
So we get, $f_c = \frac{1}{2\pi R_f C_f} = 139.78\text{Hz}$

Table 3: Observation table for the active low-pass filter

Sl. No.	Frequency f	V_{in} (V)	V_{out} (V)	Gain ($V_{\text{out}}/V_{\text{in}}$)	Gain (dB)	Sl. No.	Frequency f	V_{in} (V)	V_{out}	Gain ($V_{\text{out}}/V_{\text{in}}$)	Gain (dB)
1	10.55 Hz	2.10	20.8	9.90	45.86	18	862.1 Hz	2.10	4.00 V	1.90	12.89
2	16.67 Hz	2.10	20.8	9.90	45.86	19	1.087 kHz	2.10	3.20 V	1.52	8.42
3	22.12 Hz	2.12	20.8	9.81	45.67	20	1.404 kHz	2.10	2.20 V	1.05	0.93
4	30.86 Hz	2.10	20.6	9.81	45.67	21	1.923 kHz	2.10	1.72 V	0.82	-3.99
5	44.25 Hz	2.10	20.0	9.52	45.08	22	2.660 kHz	2.10	1.28 V	0.61	-9.90
6	65.79 Hz	2.12	19.4	9.15	44.28	23	3.049 kHz	2.16	1.16 V	0.54	-12.43
7	87.72 Hz	2.14	18.4	8.60	43.03	24	3.650 kHz	2.16	940 mV	0.44	-16.64
8	109.6 Hz	2.14	17.2	8.04	41.68	25	4.348 kHz	2.18	800 mV	0.37	-20.05
9	140.6 Hz	2.14	15.6	7.29	39.73	26	6.250 kHz	2.18	580 mV	0.27	-26.48
10	168.9 Hz	2.14	14.2	6.64	37.85	27	8.772 kHz	2.20	420 mV	0.19	-33.12
11	183.8 Hz	2.10	13.2	6.29	36.77	28	10.00 kHz	2.18	360 mV	0.17	-36.02
12	204.9 Hz	2.12	12.8	6.04	35.96	29	13.16 kHz	2.20	320 mV	0.15	-38.56
13	231.5 Hz	2.12	11.6	5.47	33.99	30	14.29 kHz	2.20	280 mV	0.13	-41.23
14	257.7 Hz	2.10	10.8	5.14	32.75	31	16.67 kHz	2.10	228 mV	0.11	-44.41
15	308.6 Hz	2.12	9.60	4.53	30.21	32	18.12 kHz	2.10	216 mV	0.10	-45.49
16	490.8 Hz	2.10	6.40	3.05	22.29	33	19.53 kHz	2.10	200 mV	0.10	-47.03
17	675.7 Hz	2.10	4.80	2.29	16.53	34	21.55 kHz	2.10	180 mV	0.09	-49.13

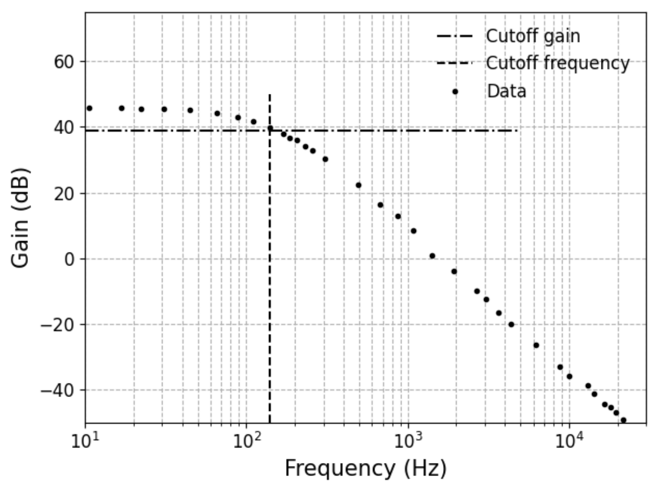


Figure 4: The frequency response obtained for the low-pass active filter

5 Results

The OPAMP differentiator circuit was implemented using IC 741, and its input–output characteristics were studied for various waveform inputs (see figure 2). For a sinusoidal input, the output was also sinusoidal but shifted in phase by -90°, consistent with theoretical predictions. When a triangular wave was applied, the output became a square wave, while a square wave input produced sharp positive and negative spikes at the transition points. These observations confirm that the output voltage of the differentiator is proportional to the time derivative of the input signal which is in agreement with the theoretical expression $V_{\text{out}} = -R_f C_{\text{in}} \frac{dV_{\text{in}}}{dt}$.

In the integrator circuit, when a sinusoidal input was applied, the output waveform remained sinusoidal but phase-shifted by 90°. A triangular wave input produced a parabolic waveform at the output, while a square wave input gave a triangular output (see figure 3). These results validate the theoretical expression $V_{\text{out}} = -\frac{1}{R_1 C_f} \int V_{\text{in}} \, dt$, confirming that the circuit performs an integration operation on the input voltage.

The active low-pass filter was then tested by varying the input signal frequency and recording the corresponding output amplitude. Using component values $R_f = 100.9$ kΩ and $C_f = 11.29$ nF, the theoretical cut-off frequency was calculated to be $f_c = 1/(2\pi R_f C_f) =$

139.78 Hz. The cutoff frequency obtained from the graph plot 4 is:

$$f_c = 140.6 \text{ Hz}$$

which is close the theoretical prediction.

The experimental data, summarized in Table 3, show that the gain remained nearly constant for frequencies below approximately 1 kHz and began to fall thereafter. The gain decreased by about 3 dB near 139.78 kHz, matching the theoretical cutoff frequency. The corresponding frequency response plot is shown in Figure 4.

6 Discussion

For the differentiator, the linear increase of gain with frequency (as per equation 3) explains why higher-frequency components dominate the output. This also accounts for the appearance of sharp spikes when a square wave is applied — the circuit differentiates the step transitions of the waveform. However, excessive high-frequency gain can introduce instability or noise sensitivity, which is why a small resistor was added in parallel to the feedback capacitor to limit the bandwidth.

For the integrator, the gain decreases inversely with frequency (equation 6), making the circuit act as a low-pass filter. The phase shift and waveform transformations were consistent with integration behavior.

The active low-pass filter exhibited a nearly flat passband up to the cutoff frequency and then an exponential falloff in gain, confirming the theoretical response of a first-order low-pass filter. The experimentally determined cutoff frequency closely matched the calculated value ($f_c \approx 139.78$ Hz). Minor deviations can be attributed to tolerances in resistor and capacitor values and the non-ideal frequency response of the OPAMP (finite slew rate and bandwidth).

7 Conclusion

The OPAMP differentiator circuit was found to produce an output proportional to the time derivative of the input voltage, confirming differentiating behavior.

The OPAMP integrator circuit produced an output proportional to the time integral of the input voltage, thereby acting as an active low-pass filter.

The active low-pass filter exhibited a cutoff frequency at approximately 140.6 Hz, in close agreement with theoretical calculations.

Thus, the experiment successfully verified the working principles of OPAMP as a differentiator, integrator, and active low-pass filter.

8 Precautions

1. All connections must be made only after switching off the power supply to avoid damage to the OPAMP and other circuit components.
2. Proper common grounding must be ensured throughout the circuit to avoid noise, oscillations, and unwanted interference.
3. The frequency of the input signal must be increased gradually during measurements to avoid missing the cutoff region in the filter experiments.