Integrators, differentiators, and simple filters

1. Objectives

- Analyze and measure characteristics of circuits built with opamps.
- Design and test circuits with opamps.
- Plot gain vs. frequency to understand circuit operations.
- Use SPICE to verify circuit designs.

2. Reference

The opamp characteristics and circuits are covered in the textbook. Make sure you know how to analyze circuits using the simple ideal opamp model.

Review the usage of the programmable power supply that can set two supply values (e.g. +12 V and –12 V). The convention is to use VCC to denote the positive supply and VEE to denote the negative supply.

The only knowledge required for this experiment is: time-domain analysis, basic opamp circuit analysis, and impedance of components. The technique to plot gain as function of frequency is described in the Discussion section below. No knowledge of filters is required.

3. Circuits

You will analyze, design, and simulate the circuits below in various parts of this laboratory.

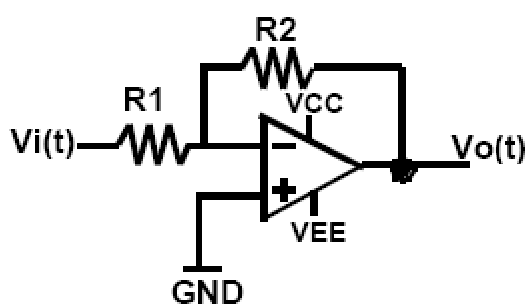

Figure 1. Inverting amplifier.

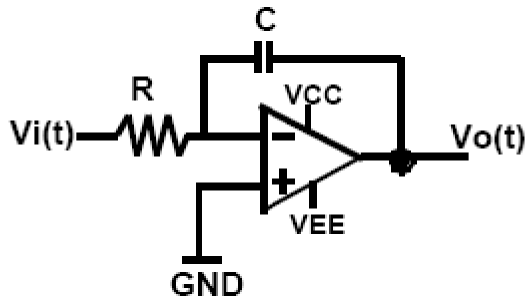

Figure 2. Simple integrator.

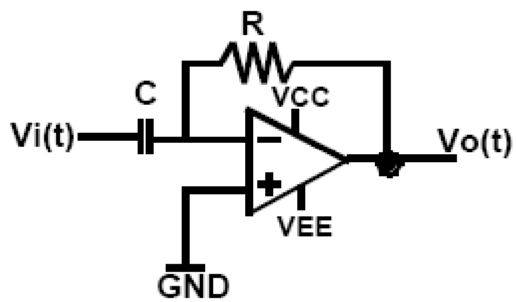

Figure 3. Simple differentiator.

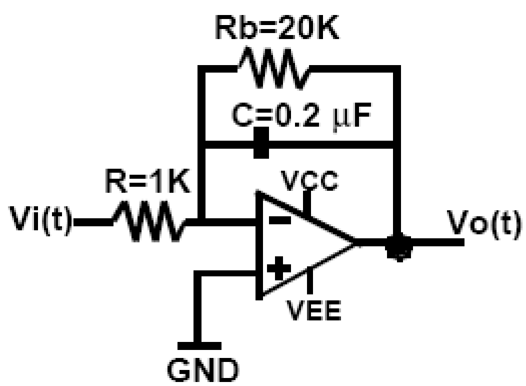

Figure 4. Integrator with shunt resistor.

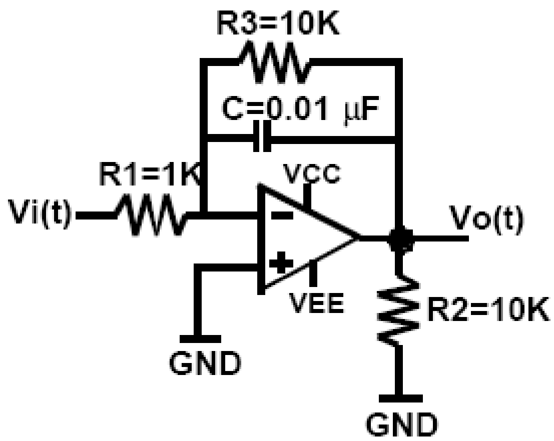

Figure 5. A low-pass filter.

4. Components and specifications

Quantity	*Description*	*Comments*
3	MC 4741C opamp	or equivalent
3	1KΩ resistor	
3	10KΩ resistor	
1	20KΩ resistor	
3	0.01 µF capacitor	
1	0.2 µF capacitor	

Opamp specifications are available from the laboratory web site of this course or manufacturers' web sites. Check your component and download the appropriate specifications.

5. Discussion

In many circuits whose signals are sine or cosine, the gain (ratio of output amplitude versus input amplitude) varies as function of the signal frequency, e.g. as shown in table 1 below. Figure 6 shows a plot of the gain versus frequency from this table, using the linear scales on both axes. Since the frequency varies over a very wide range, the plot crunches the frequency axis and does not show much about the circuit gain characteristics above the frequency 10000 Hz.

Table 1. Gain versus frequency data.

Frequency	**Vo amplitude**	**Vi amplitude**	**G= |Vo|/|Vi|**
(Hz)	**(V)**	**(V)**	**(ratio)**

10	9.998	10	0.999
20	9.993	10	0.999
50	9.960	10	0.996
100	9.845	10	0.984
200	9.406	10	0.941
500	7.172	10	0.717
1000	3.880	10	0.388
2000	1.368	10	0.137
5000	0.247	10	0.025
10000	0.063	10	0.006
20000	0.016	10	0.002
50000	0.002	10	0.0002

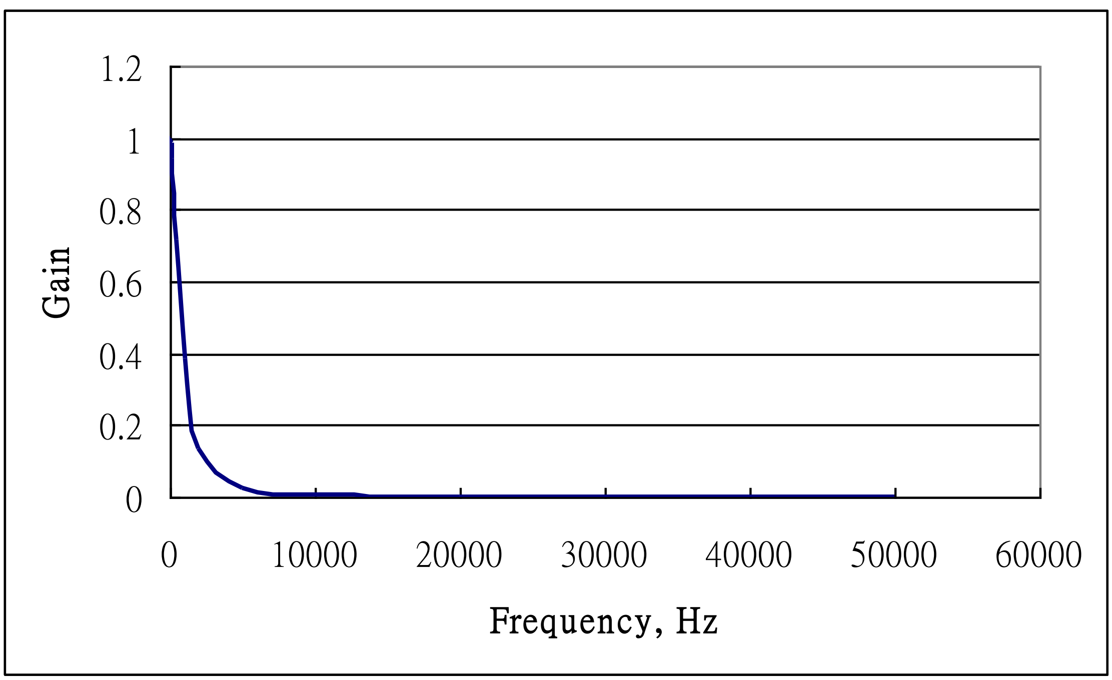

Figure 6. Linear plot of gain versus frequency.

Another way to plot is to use logarithmic scale. First, the gain values are converted to dB (decibel) using the formula:

$$G\ (dB) = 20 \log G$$

As an example, a gain G=100 is converted to G(dB)=40 dB; a gain G=0.1 is converted to G(dB)=- 20 dB. Table 2 is produced from table 1 using this conversion technique.

Table 2. Gain (dB) versus frequency data.

Frequency	**G**	**G**
(Hz)	**(ratio)**	**(dB)**
10	0.999	-0.0087
20	0.999	-0.0087
50	0.996	-0.0348
100	0.984	-0.1401
200	0.941	-0.5282
500	0.717	-2.8896
1000	0.388	-8.2234
2000	0.137	-17.2656
5000	0.025	-32.0412
10000	0.006	-44.4370
20000	0.002	-53.9794
50000	0.0002	-73.9794

Next, a semilog plot is constructed. The horizontal axis is the frequency, in logarithmic scale. The vertical axis is the gain in dB, in linear scale. The semilog plot of the data in table 2 is shown in figure 7. Once the raw data of gain versus frequency (e.g. as in table 1) is available from measurements or computations, the dB conversion and the semilog plot can be produced using software tools such as Matlab, Excel, etc.

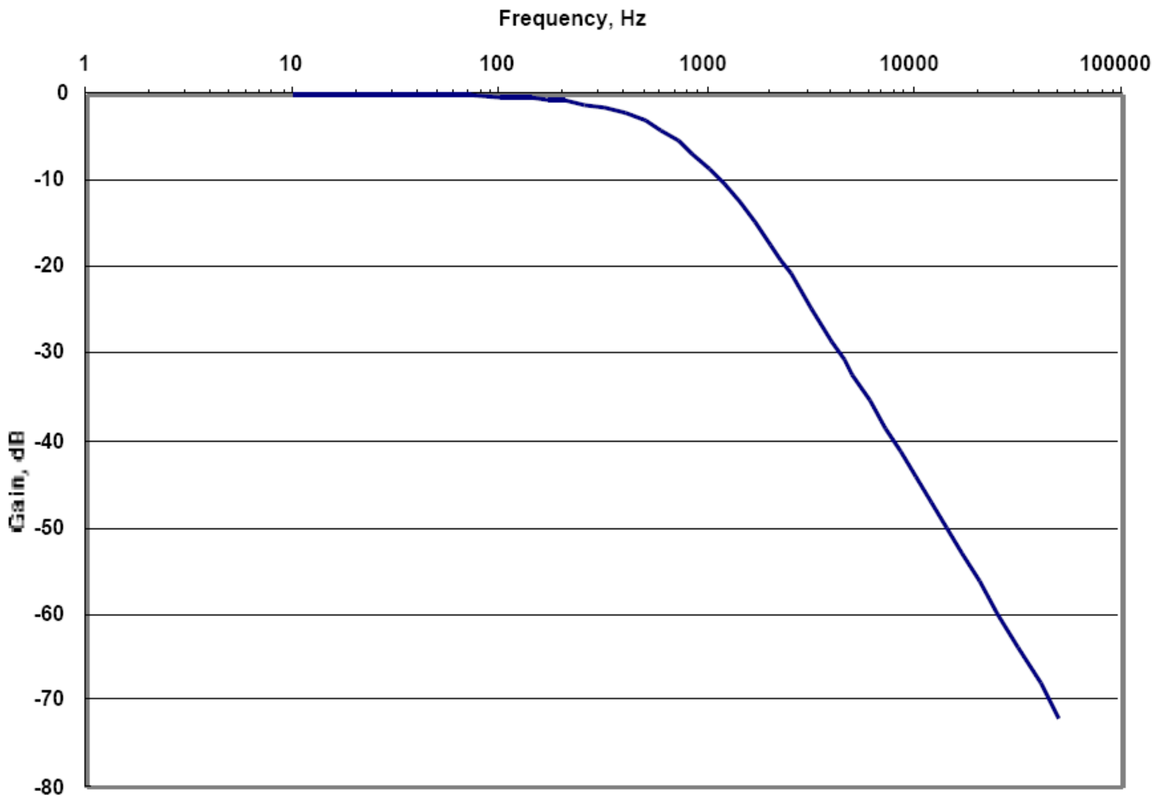

Figure 7. Semilog plot of dB gain versus frequency.

Figure 7 shows better these characteristics of the circuit: the dB gain is relatively fixed at low frequencies, the dB gain drops off linearly at high frequencies, and there is a "corner" in the gain plot between these two frequency ranges. This type of plots is regularly used to study circuit characteristics as functions of frequencies.

6. Pre-lab

6.1 Designs of simple amplifiers

For the circuit in figure 1 with power supplies VCC = 12.0 V, VEE = -12.0 V, and assuming the opamp is ideal, answer the following questions:

1. Design an inverting amplifier using one opamp and two or more resistors. Design it such that it has a gain of -10 (this gain is negative). Pick resistor values that you have in the lab kit. Include a schematic of this circuit with the component values labeled with your completed pre-lab assignment.

2. Simulate this inverting amplifier circuit with SPICE to make sure the circuit works as designed.

Look up the textbook to find a non-inverting amplifier circuit using one opamp and two or more resistors. Then assuming the opamp is ideal, answer the following questions:

3. Design a non-inverting amplifier such that it has a gain of +11 (this gain is positive). Pickresistor values that you have in the lab kit. Include a schematic of this circuit with the component values labeled with your completed pre-lab assignment.

4. Simulate this non-inverting amplifier circuit with SPICE to make sure the circuit works as designed.

6.2 Analysis of integrators and differentiators

For the circuit in Figure 2 with power supplies VCC = 12.0 V, VEE = -12.0 V, and assuming the opamp is ideal, answer the following question:

1. Derive the time-domain equation for $V_o(t)$ in terms of $V_i(t)$. Show that the circuit performs the function of an integrator.

For the circuit in Figure 3 with power supplies VCC = 12.0 V, VEE = -12.0 V, and assuming the opamp is ideal, answer the following question:

2. Derive the time-domain equation for $V_o(t)$ in terms of $V_i(t)$. Show that the circuit performs the function of a differentiator.

For the circuit in Figure 4 with power supplies VCC = 12.0 V, VEE = -12.0 V, and assuming the opamp is ideal, answer the following questions:

3. What is the low-frequency gain of this circuit?

4. For frequencies $\omega >> 1/(R_bC)$, show that the circuit performs the function of an integrator.

5. Use SPICE transient analysis to simulate this circuit in the time domain using a sine wave input with amplitude 300 mV and frequency 300 Hz. From the SPICE output plot of the input and output waveforms, confirm that this circuit is an integrator.

6. Try to explain the function of the resistor Rb in this circuit.

6.3 Analysis and simulation of an active low-pass filter

For the circuit in Figure 5 with power supplies VCC = 12.0 V, VEE = -12.0 V, assume the opamp is ideal. The input signal is:

$$v_i(t) = A\cos(\omega t)$$

where the input amplitude A is small to avoid slew-rate limitations.

The output signal for the amplitude of $v_o(t)$ in terms of the input amplitude A, input frequency ω, and circuit components R and C is

$$v_O(t) = -\frac{R_3}{R_1} A\cos(\omega t)\left(\frac{1 - j\omega C R_3}{1 + C^2\omega^2 R_3^2}\right)$$

The ratio of the output amplitude over the input amplitude is called the gain of the circuit. From above, the circuit gain in terms of input frequency ω and circuit components R and C is

$$gain = \frac{R_3}{R_1} \times \left|\frac{1 - j\omega C R_3}{1 + C^2\omega^2 R_3^2}\right| = \frac{R_3}{R_1} \times \frac{10^4}{\sqrt{10^8 + \omega^2}}$$

1. Use the numerical values of R and C in the gain equation in item 2. Plot the circuit gain (in dB values) as function of frequency (from 1 Hz to 100 KHz), using the technique described in the Discussion section.

2. Use SPICE AC analysis to simulate this circuit and generate the gain plot. Compare the SPICE gain plot with your plot in item 1 above. Explain any differences.

3. If the input signal has low frequency, what is the expected gain from these plots in items 1 and 2 above? If the input signal has high frequency, what is the expected gain from these plots? Based on these gain values, explain why the circuit is named “low-pass” filter.

4. Note that this circuit is topologically similar to the integrator circuit. Try to explain why these two types of circuits are similar.

7. Experimental procedures

7.1 Instruments needed for this experiment

The instruments needed for this experiment are: a power supply, a multimeter, a function generator and an oscilloscope.

7.2 Inverting amplifiers

Build the circuit in Figure 1 using power supplies +12.0 V, - 12.0 V and the resistor values from your design in the Pre-lab, section 6.1 item 1.

1. Use a sine wave input with small amplitude so that the output is not affected by the slew rate in this part. Set ch1 to 1X probe gain and DC coupling. From the starting input frequency of 20 Hz and varying it using 2-5-10 sequence up to 1 MHz (i.e. set input frequency to 10 Hz, 20 Hz, 50 Hz, 100 Hz, 200 Hz, … up to 1 MHz), measure the experimental values of the gain of this circuit at each frequency. Record them in a table for later data analysis.

2. **Save a screenshot** from the scope display with both waveforms at the frequency 100 KHz. Turn this screenshot in as part of your lab report.

Turn in: a table of gain vs frequency and a screenshot

7.3 Integrators

1. Build the circuit in Figure 4 with power supplies +12.0 V, - 12.0 V. Apply a sine wave input signal with amplitude 600 mV, DC offset 0V and frequency 1200 Hz. Display the input signal on channel 1 of the oscilloscope.

2. Display V_o on Channel 2 and adjust the timebase to display 2 to 3 complete cycles of the signals. Set both ch-1 and ch-2 to 1X probe gain and DC coupling.

3. **Save a screenshot** from the scope display with both waveforms to confirm that the circuit is an integrator. Turn this screenshot in as part of your lab report.

4. Change the input signal to a square wave with the same 600 mV amplitude, DC offset 0V, and frequency 1200 Hz. Save a screenshot from the scope display with both waveforms to confirm that the circuit is still an integrator. Turn this screenshot in as part of your lab report.

5. Repeat item 4 above using a triangular input signal with same amplitude and frequency. Turn this screenshot in as part of your lab report.

6. Now change the input back to a sine wave as in item 1. Remove the resistor R_b while running the function generator and Data capture. Align two waveforms so that is will be easier to see the output. What happens to the output signal? Explain the phenomenon you observe on the oscilloscope. Re-insert the resistor R_b and verify that the circuit functions as designed.

Turn in: screenshots and answer #6

7.4 Low-pass filters

1. Build the circuit in Figure 5 with power supplies +12.0 V, - 12.0 V. Use a sine wave of amplitude 200 mV as an input signal (see item 2 below for frequency) and display both the input and output signals on the oscilloscope (2 to 3 complete cycles). Set probe gain 1X and DC coupling.

2. Vary the input signal frequency in 2-5-10 sequence from 20 Hz to 100 KHz. At each frequency, measure the gain of the circuit, using the data from the oscilloscope display. Keep this data in a table for later plotting.

Turn in: a table of gain vs frequency

8. Data analysis

8.1 Inverting amplifiers

1. Compare the experimental gain measured in section 7.2 item 1 with the calculated gain in the pre-lab and with the gain as simulated by SPICE. Explain any difference between these values. 2. From the table of data in section 7.2 item 1, plot the gain of this circuit as dB versus frequency, using the technique described in the Discussion section.

8.2 Integrators

1. Explain any difference between the SPICE output in section 6.2 item 5 and the experimental data in section 7.3 item 3.

2. With the experimental observation in section 7.3 item 6, explain the function of the resistor R_b.

8.3 Low-pass filters

1. From the data in section 7.4 item 2, plot the gain (in dB) of the circuit as function of frequency(using the technique described in the Discussion section) and compare it with the plots in section6.3 item 3 and in section 6.3 item 4 (SPICE plot). Explain any differences between these 3 plots.