ECEN 325 Lab 5: Operational Amplifiers – Part III

Objectives

The purpose of the lab is to study some of the opamp configurations commonly found in practical applications and also investigate the non-idealities of the opamp such as finite Gain-Bandwidth product and slew rate limitations. The circuits studied will include an integrator, a differentiator, a non-inverting amplifier and a unity-gain buffer.

Introduction

Integrator

The circuit in Fig. 1 is the lossless inverting integrator, which generates an output signal that corresponds to the integral of the input signal over time.
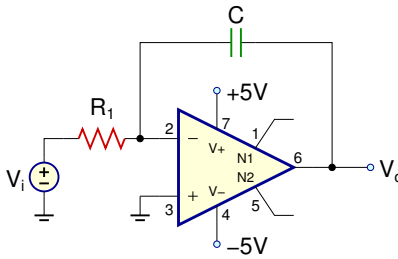

Figure 1: Inverting integrator circuit

In the frequency domain, the output voltage is described as:

$$V_o = -\frac{1}{sR_1 C} V_i \tag{1}$$

Notice that the gain V_o/V_i is theoretically infinite at DC ($s = 0$), hence any small DC signal at the input will saturate the opamp output over time. In a practical integrator circuit, a large resistor in parallel with the capacitor is required to prevent the capacitor from storing charge due to offset currents and voltages at the input. This configuration is known as "lossy" integrator or a first-order lowpass circuit, which is shown in Fig. 2. The output voltage is now given by the following expression:

$$V_o = -\frac{R_2/R_1}{1 + sR_2 C} V_i \tag{2}$$

The DC gain is now finite and determined by the ratio of the two resistors.
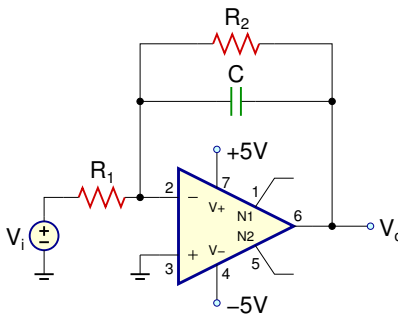

Figure 2: Lossy integrator circuit

Differentiator

As the counterpart of the integrator, the differentiator takes the derivative of the input signal. This configuration is shown in Fig. 3.
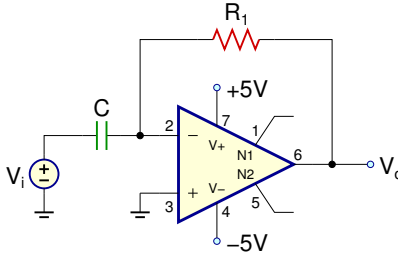

Figure 3: Inverting differentiator circuit

The output voltage in Fig. 3 can be obtained as

$$V_o = -sCR_1 V_i \qquad (3)$$

Ideally, the output voltage becomes very large at very high frequencies. However, due to opamp's gain limitation at high frequencies, differentiator's gain also starts to decrease, deviating from the ideal behavior. To limit the high-frequency gain to a known value, a pseudo differentiator circuit as shown in Fig. 4 can be used.
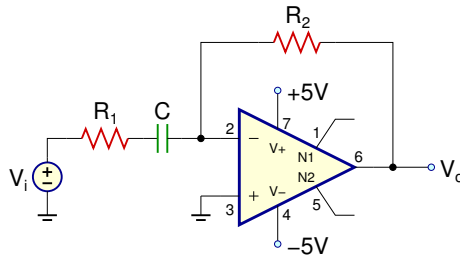

Figure 4: Pseudo differentiator circuit

The output voltage in Fig. 4 can be found as

$$V_o = -\frac{R_2}{R_1} \frac{s}{s + \dfrac{1}{R_1 C}} V_i \qquad (4)$$

Low frequency input signals dominate integrator's output due to higher gain, whereas high frequency signals are more dominant for differentiators for the same reason. Due to the limited high frequency capabilities of the opamps, differentiators are more difficult to build in practice. In addition, integrator functionality is tolerant to noise at the input, whereas addition of noise to the input signal makes the differentiation operation unreliable. Therefore, in most of the practical systems such as filters, integrators are used instead of differentiators.

Non-Idealities of the Opamp

Finite Gain-Bandwidth (GBW) Product:

The open-loop gain of the opamp decreases when frequency increases following the roll-off of a single pole system. However, the product of open-loop DC gain and the 3-dB frequency (bandwidth) is a constant, which is defined as the Gain-Bandwidth product (GBW). For the UA741, GBW is about 1.2MHz. Finite GBW of the opamp limits the bandwidth of closed-loop amplifier configurations.

Assuming a finite GBW of ω_t, the frequency dependent gain of the non-inverting amplifier shown in Fig. 5 is given by

$$\frac{V_o}{V_i} = \frac{G_o}{1 + \dfrac{s}{\omega_o}} \qquad (5)$$

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where G_o is the DC gain of the amplifier given by $(1 + R_2/R_1)$ and $\omega_o = \omega_t/G_o$.
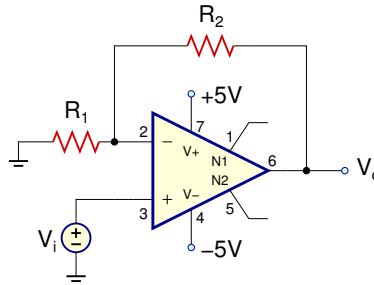

Figure 5: Non-inverting amplifier configuration

Slew Rate

An ideal opamp is capable of following the input signal no matter how fast the input changes. In a real 741, the output rise/fall transient cannot exceed a maximum slope; the maximum rate of change of the output voltage as a function of time is defined as the slew rate. Applying signals with transients that exceed this limit results in distorted output signals. To avoid distortion due to slew rate limitations, maximum rate of change of output must be kept less than the slew rate specifications of the opamp. The slew rate can be measured by applying a large square waveform at the input. The slope of the rise time at the output is the slew rate.
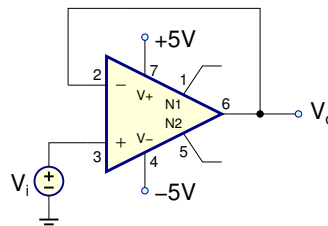

Figure 6: Unity-gain buffer configuration

Calculations

Lossy Integrator

1. For the lossy integrator in Fig. 2, derive the time-domain equation for the output in terms of the input.

2. Find R_1 to have a low-frequency gain of -22 if $R_2 = 22k\Omega$ and $C = 220nF$, and calculate the 3-dB frequency.

3. Sketch the magnitude and phase Bode plots for the transfer function V_o/V_i.

4. Calculate $V_o(t)$ for $V_i(t) = 0.5\sin(2\pi 1000t)$.

5. Sketch the output waveform if the input is a 500mV 1kHz square wave signal.

Pseudo Differentiator

1. For the first order high-pass filter in Fig. 4, derive the time-domain equation for the output in terms of the input.

2. Find R_2 to have a high-frequency gain of -22 if $R_1 = 1k\Omega$ and $C = 33nF$, and calculate the 3-dB frequency.

3. Sketch the magnitude and phase Bode plots for the transfer function V_o/V_i.

4. Calculate $V_o(t)$ for $V_i(t) = 0.1\sin(2\pi 1000t)$.

5. Sketch the output waveform if the input is a 100mV 1kHz triangular wave signal.

Finite GBW Limitations

1. For the non-inverting amplifier in Fig. 5, assume $R_1 = 1k\Omega$. Find the values of R_2 to set the low-frequency gain to 23, 57, and 83.

2. Find the transfer function $V_o/V_i(s)$ for each gain value.

3. Sketch the magnitude Bode plots of the three transfer functions on the same plot.

Slew Rate Limitations

1. For the unity-gain buffer in Fig. 6, find the transfer function $V_o/V_i(s)$, and sketch the magnitude Bode plot.

2. If the slew rate of the opamp is $0.5V/\mu s$, find the maximum frequency of the 1V sine wave input signal before the output is distorted.

3. If the slew rate of the opamp is $0.5V/\mu s$, find the maximum amplitude of the 75kHz sine wave input signal before the output is distorted.

Simulations

For all simulations, provide screenshots showing the schematics and the plots with the simulated values properly labeled.

Lossy Integrator

1. Draw the schematics for the lossy integrator in Fig. 2 with the calculated component values.

2. Obtain the magnitude and phase **Bode plots** of the transfer function using **AC simulation**. Measure the low-frequency gain, 3-dB frequency, and the magnitude and phase of the transfer function at 1kHz.

3. Apply a 1kHz 500mV sine wave signal to the input V_i and obtain the **time-domain waveforms** for the input and output voltages using **transient simulation**. Measure the magnitudes of the input and the output voltages, and the phase difference between them.

4. Apply a 1kHz 500mV square wave signal to the input V_i and obtain the **time-domain waveforms** for the input and output voltages using **transient simulation**. Measure the peak-to-peak voltage of the output.

Pseudo Differentiator

1. Draw the schematics for the pseudo differentiator in Fig. 4 with the calculated component values.

2. Obtain the magnitude and phase **Bode plots** of the transfer function using **AC simulation**. Measure the low-frequency gain, 3-dB frequency, and the magnitude and phase of the transfer function at 1kHz.

3. Apply a 1kHz 100mV sine wave signal to the input V_i and obtain the **time-domain waveforms** for the input and output voltages using **transient simulation**. Measure the magnitudes of the input and the output voltages, and the phase difference between them.

4. Apply a 1kHz 100mV triangular wave signal to the input V_i and obtain the **time-domain waveforms** for the input and output voltages using **transient simulation**. Measure the peak-to-peak voltage of the output.

Finite GBW Limitations

1. Draw the schematics for the non-inverting amplifier in Fig. 5.

2. Obtain the magnitude and phase **Bode plots** of the transfer functions using **AC simulation** with **parameter sweep**, where the resistor R_2 is swept to realize the three gain values 23, 57, and 83. Group all three traces in one plot as in your sketch.

3. Measure the low-frequency gain and 3-dB frequency for each value of R_2.

Slew Rate Limitations

1. Draw the schematics for the unity-gain buffer in Fig. 6 with a load of $2.2k\Omega$ in parallel with 100pF at the output.

2. Obtain the magnitude and phase **Bode plots** of the transfer function using **AC simulation**. Measure the low-frequency gain, 3-dB frequency, and the magnitude of the transfer function at 75kHz and 150kHz.

3. Apply a 75kHz 1V sine wave signal to the input V_i and obtain the **time-domain waveforms** for the input and output voltages using **transient simulation**. Perform **Fourier simulation** to measure the **total harmonic distortion (THD)** on the output waveform.

4. Repeat the previous step for 75kHz 2V sine wave, and 150kHz 1V sine wave input signals.

Measurements

For all measurements, provide screenshots showing the plots with the measured values properly labeled.

Lossy Integrator

1. Build the lossy integrator in Fig. 2 with the simulated component values.

2. Obtain the magnitude and phase **Bode plots** of the transfer function using the **network analyzer**. Measure the low-frequency gain, 3-dB frequency, and the magnitude and phase of the transfer function at 1kHz.

3. Apply a 1kHz 500mV sine wave signal to the input V_i and obtain the **time-domain waveforms** for the input and output voltages using the **scope**. Measure the magnitudes of the input and the output voltages, and the phase difference between them.

4. Apply a 1kHz 500mV square wave signal to the input V_i and obtain the **time-domain waveforms** for the input and output voltages using the **scope**. Measure the peak-to-peak voltage of the output.

5. Remove the resistor R_2 and observe what happens to the output signal. Comment on the result.

Pseudo Differentiator

1. Build the pseudo differentiator in Fig. 4 with the simulated component values.

2. Obtain the magnitude and phase **Bode plots** of the transfer function using the **network analyzer**. Measure the low-frequency gain, 3-dB frequency, and the magnitude and phase of the transfer function at 1kHz.

3. Apply a 1kHz 100mV sine wave signal to the input V_i and obtain the **time-domain waveforms** for the input and output voltages using the **scope**. Measure the magnitudes of the input and the output voltages, and the phase difference between them.

4. Apply a 1kHz 100mV triangular wave signal to the input V_i and obtain the **time-domain waveforms** for the input and output voltages using **scope**. Measure the peak-to-peak voltage of the output.

Finite GBW Limitations

1. Build the non-inverting amplifier in Fig. 5 with $R_1 = 1k\Omega$ and R_2 corresponding to the gain of 23.

2. Obtain the magnitude and phase **Bode plots** of the transfer function using the **network analyzer**.

3. Measure the low-frequency gain and 3-dB frequency.

4. Repeat the steps 1, 2, and 3 using R_2 corresponding to the gain values of 57 and 83.

Slew Rate Limitations

1. Build the unity-gain buffer in Fig. 6 with a load of $2.2k\Omega$ in parallel with 100pF at the output.

2. Obtain the magnitude and phase **Bode plots** of the transfer function using the **network analyzer**. Measure the low-frequency gain, 3-dB frequency, and the magnitude of the transfer function at 75kHz and 150kHz.

3. Apply a 75kHz 1V sine wave signal to the input V_i and obtain the **time-domain waveforms** for the input and output voltages using the **scope**. Measure the **total harmonic distortion (THD)** on the output waveform using the **spectrum analyzer**.

4. Repeat the step 3 for 75kHz 2V sine wave, and 150kHz 1V sine wave input signals.

Report

1. Include calculations, schematics, simulation plots, and measurement plots.

2. Prepare a table showing calculated, simulated and measured results.

3. Compare the results and comment on the differences.

Demonstration

1. Build the circuits in Figs. 2, 4, 5 and 6 on your breadboard, and bring it to your lab session

2. Your name and UIN must be written on the side of your breadboard.

3. Submit your report to your TA at the beginning of your lab session.

4. For the lossy integrator in Fig. 2:

   - Show the frequency response using the network analyzer.
   - Show the time-domain output for a square-wave input using the scope.

5. For the pseudo differentiator in Fig. 4:

   - Show the frequency response using the network analyzer.
   - Show the time-domain output for a triangle-wave input using the scope.

6. For the non-inverting amplifier in Fig. 5:

   - Use $R_1 = 1k$ and R_2 determined by your TA (within 30k-50k), and estimate the gain and bandwidth.
   - Show frequency response using the network analyzer and measure the gain and bandwidth.

7. For the unity-gain buffer in Fig. 6:

   - Show the time-domain output for a +2V to -2V square-wave input using the scope.
   - Measure the slew rate from the slope of the output waveform.