EE203 - Electrical Circuits Laboratory

Experiment - 8 Simulation
Operational Amplifier Applications

Objectives

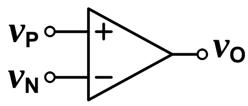
1. Observe operational amplifier circuits working as comparators, integrators and differentiators.

Background

Comparator

A comparator generates an output that switches between two voltage levels according to the relative voltage between its inputs.

If $v_P > v_N$ then $v_O = V_H$
otherwise $v_O = V_L$

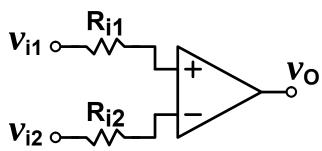


An operational amplifier works like a comparator when it is used without any feedback circuit. The operational amplifier output saturates either at V_H near the positive supply or at V_L near the negative supply voltage, because the differential input $v_P - v_N$ is amplified with a very high voltage gain.

Comparators can be used to make decisions in digital circuits according to the voltage level of an analog input. The output voltages, V_L and V_H, should correspond to either "**0**" or "**1**" digital signal levels, but in practice this may not be achieved by using ordinary opamps. There are specifically designed comparator ICs, and usage of ordinary opamps to replace these ICs is not suggested because of the following reasons.

- Supply requirements and output voltage range of ordinary opamps are not compatible with the common digital circuits.
- Saturation of opamp output causes additional time delays and limits the operation frequency.

The comparator circuit shown on the right has resistors to limit input currents of the opamp. These resistors prevent accidental damage to the opamp, in case there are unpredictable voltage changes at v_{i1} and v_{i2} inputs.

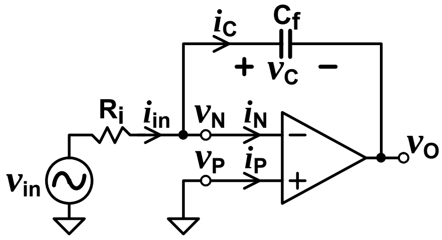


Integrator

An operational amplifier functions as an integrator when a capacitor is used in the feedback path as shown below. The output voltage v_O is proportional to the time integral of v_{in}, and this relation can be established by considering idealized opamp characteristics as follows.

$$\frac{v_{in}}{R_i} = i_{in} = i_C \quad \text{(because } v_P - v_N \simeq 0 \text{ and } i_N \simeq 0\text{)}$$

$$v_O = -v_C \quad \text{(because } v_P - v_N \simeq 0\text{)}$$



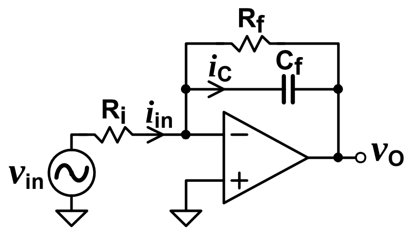
If these equations are combined assuming that initially $v_O(0) = -v_C(0) = 0$ **V** then:

$$v_O(t) = -\frac{1}{C_f}\int_{t'=0}^{t} i_C(t')\,dt' = -\frac{1}{C_f}\int_{t'=0}^{t} i_{in}(t')\,dt'$$

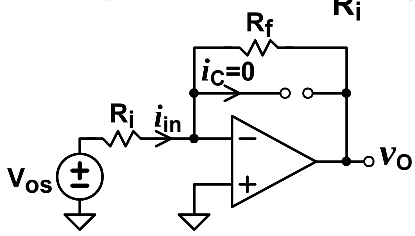
$$v_O(t) = -\frac{1}{R_i C_f}\int_{t'=0}^{t} v_{in}(t')\,dt'$$

If we look at the steady state response when v_{in} is a constant DC signal, then we see that the circuit has a nearly infinite gain. If we assume that the capacitor voltage v_C is constant, then i_C is zero, which means there is no feedback in the circuit. Consequently, the opamp output saturates near the positive or negative supply voltage as a result of any DC offset at the input, no matter how small the offset is. In practice, a feedback resistor $\mathbf{R_f}$ is added to avoid this problem.

Integrator with feedback resistor:



DC response: $v_O = -\frac{R_f}{R_i} V_{os}$



The components of an integrator can be selected following these steps.

1. Choose $\mathbf{R_i}$ big enough (i.e. **>1 kΩ** and **<100 kΩ**), so that the v_{in} source can easily drive $\mathbf{R_i}$, and opamp output can easily drive the feedback circuit. Remember that every source has a finite output resistance $\mathbf{R_o}$, and an ordinary opamp can only support output currents in the order of a few **mA**. On the other hand, if $\mathbf{R_i}$ is too big (i.e. **1 MΩ**), then you will face problems due to opamp bias or offset currents as small as **1 μA**.

2. Choose $\mathbf{C_f}$ to obtain the required v_O output range depending on the amplitude and frequency of v_{in}. $\mathbf{R_i}$ and $\mathbf{C_f}$ determine the gain factor, $1/R_iC_f$, that relate v_O to time integral of v_{in}.

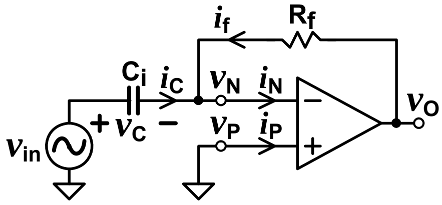
3. Choose $\mathbf{R_f}$ big enough to obtain a feedback time constant $\tau_{fb} = R_fC_f$ longer than period $\mathbf{T_{prd}}$ of the v_{in} input signal. A better integration accuracy is obtained when $R_fC_f \gg T_{prd}$. Also remember that $\mathbf{R_f}$ determines the DC offset at v_O. For example, if $R_f/R_i = 10$, and input offset is **0.1 V**, then DC offset at v_O will be **1.0 V**.

Differentiator

A differentiator implements the reverse of integration function, where the output is proportional to the time derivative of the input signal. An operational amplifier functions as an differentiator when a capacitor is used in the input path as shown below. v_O is related to the time derivative of v_{in} as follows.

$$v_{in} = v_C \quad \text{(because } v_P - v_N \simeq 0\text{)}$$

$$i_C = C_i \frac{dv_C}{dt} = -i_f = -\frac{v_O}{R_f} \quad \text{(because } i_N \simeq 0\text{)}$$



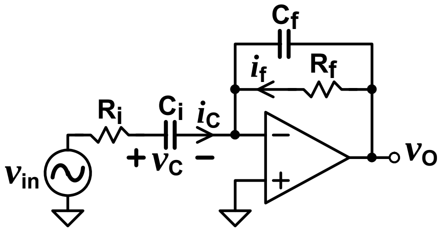
If these equations are combined then:

$$v_O(t) = -R_f C_i \frac{dv_C}{dt} = -R_f C_i \frac{dv_{in}}{dt}$$

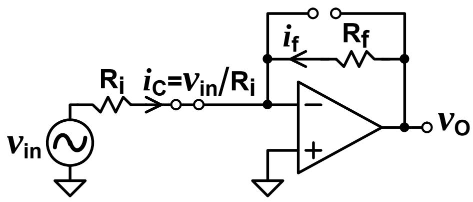
The differentiator does not have an offset problem, since DC feedback is established through **R_f**. DC component of v_{in} is filtered out by **C_i**, and the DC voltage at the opamp input is always **0 V**. In other words, the opamp behaves like a unity gain buffer with **0 V** input.

High frequency instability is the main problem in differentiators. The input capacitor **C_i** behaves as a short circuit at high frequencies that results in a very high closed loop gain. This high gain causes high frequency oscillations and additional noise at the opamp output. As a solution, a series input resistance **R_i** is included to limit the AC closed loop gain as shown in the following circuit. Furthermore, a compensation capacitor **C_f** may be added in parallel to the feedback resistor to decrease the maximum operating frequency of the opamp.

Differentiator with input resistor and compensation capacitor:



High frequency AC response with a small **C_f**: $v_O = -\frac{R_f}{R_i} v_{in}$



Constraints for selection of differentiator components are similar to those described for design of integrators:

1. Choose R_f big enough, considering the same loading conditions specified for the integrator.

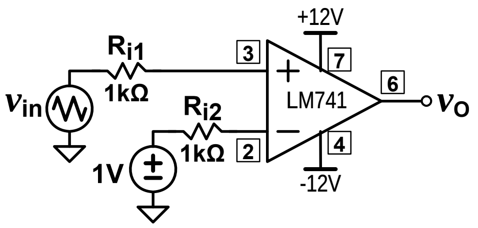
2. Choose C_i to obtain the required v_O output range depending on the amplitude and maximum rate of change of v_{in}. **R_f** and **C_i** determine the gain factor, **R_fC_i**, that relate v_O to time derivative of v_{in}.

3. Choose R_i small enough to obtain an input time constant **$\tau_{in} = R_iC_i \ll T_{prd}$**, where, **$T_{prd}$** is the period of v_{in} input signal.

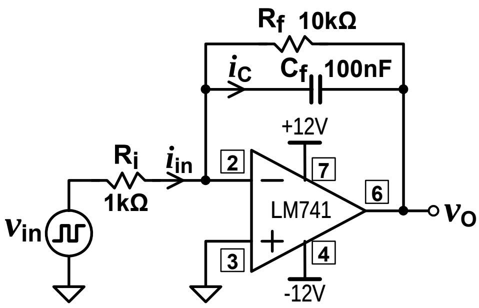
4. Theoretically, **C_f** should be small enough to obtain a feedback time constant **$\tau_{fb} = R_fC_f \ll T_{prd}$**, where, **$T_{prd}$** is the period of v_{in} input signal. In practice, selection of **C_f** depends on the maximum operating frequency or ***bandwidth*** of the opamp. **C_f** is not necessary for a low-frequency opamp in ordinary applications. Usually a small capacitor between **10 pF** and **100 pF** is sufficient to stabilize a high-frequency opamp.

Preliminary Work

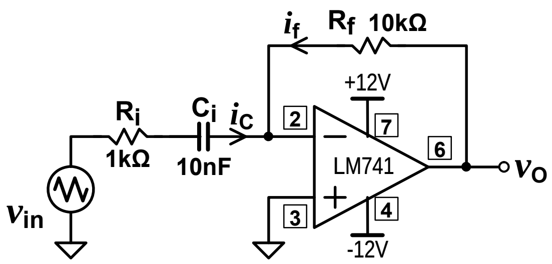
1. Draw v_{in} and the expected v_O waveforms when v_{in} is a **500 Hz**, **10 V**p-p triangular signal in the following comparator circuit. Indicate v_{in} voltage levels and relative v_O switcing times corresponding to every change at v_O.



2. Draw the expected v_O waveform when v_{in} is a **1 kHz**, **4 V**p-p square wave signal in the following integrator circuit assuming that $\mathbf{R_fC_f \gg 1}$ **ms**.



3. Draw the expected v_O waveform when v_{in} is a **1 kHz**, **10 V**p-p triangular signal in the following differentiator circuit assuming that $\mathbf{R_iC_i \ll 1}$ **ms**.

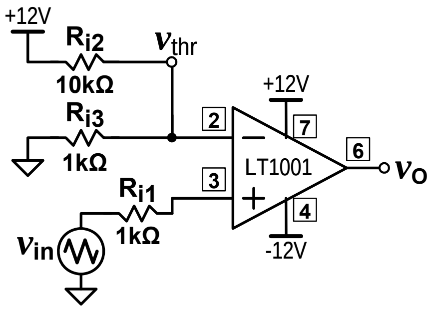


Procedure

LT1001 operational amplifier model will be used instead of **LM741** to obtain the simulation results on LTspice. Although **LT1001** has much better characteristics compared to **LM741**, both of the devices satisfy the basic requirements of an operational amplifier and the results obtained in the following steps will not be significantly different.

1. Build the circuit given on the right. Place separate DC voltage sources to obtain **+12 V** and **–12 V** supplies required for the opamp.

It is practical to connect these sources to net labels for each supply and use the same net labels for the opamp supply connections.



Set the v_{in} signal source to obtain **500 Hz triangular** wave with **10 V**p-p amplitude. Use a pulse voltage source as v_{in} with the timing parameters, `Trise = 1m`, `Tfall = 1m`, `Ton = 0`, and `Tperiod = 2m` to obtain the triangular waveform.

1.1 Display v_{in}, v_O and v_{thr} waveforms. Record the v_O voltage levels for every change at v_O and determine timing of v_O zero-cross points relative to the crossing points of v_{in} and v_{thr}. Calculate the slew rate of v_O according to the time difference corresponding to **+/-10 V** voltage change in the middle of v_O transitions.

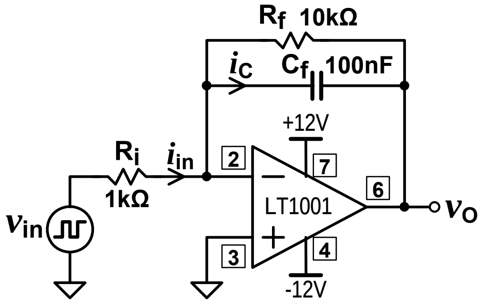
Change in v_O (**V to V**)	relative time (**μs**) of v_O zero-cross	v_O slew rate (**V/μs**)

1.2 Replace **LT1001** with an **AD795 FET-input** opamp and repeat the measurements in the previous step.

Change in v_O (**V to V**)	relative time (**μs**) of v_O zero-cross	v_O slew rate (**V/μs**)

1.3 Explain differences between the v_{thr} waveforms and the measurements obtained with **LT1001** and **AD795** opamps.

2. Build the integrator circuit given on the right, and set the v_{in} signal source to obtain **500 Hz square wave** with **2 V**p-p amplitude. Use a pulse voltage source as v_{in} with the timing parameters, `Trise = 1u`, `Tfall = 1u`, `Ton = 999u`, and `Tperiod = 2m` to obtain the square waveform.



2.1 Display v_{in} and v_O waveforms. Measure the peak-to-peak output voltage for the following v_{in} frequency settings.

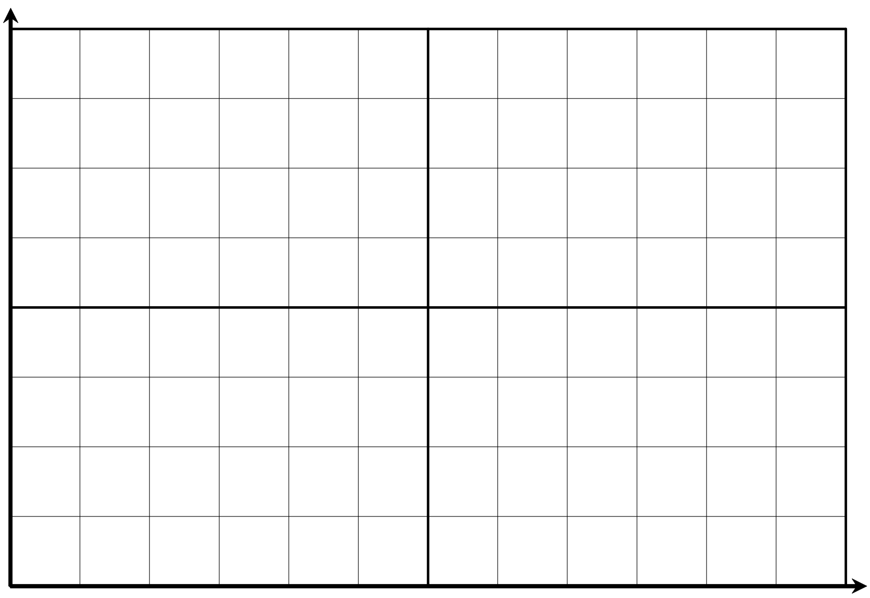
Note that you should increase the simulation time to see the output waveform with the final offset value, and zoom into the steady state response.

v_{in} square wave frequency	v_O amplitude (**V**p-p)
500 Hz	
1 kHz	
2 kHz	

2.2 Set v_{in} frequency to **1 kHz**, and add another voltage source to obtain the following DC offset values at v_{in} by using the oscilloscope. Measure and record the corresponding DC offset values at v_O.

v_{in} offset (**V**)	v_O offset (**V**)
0.0	
-0.5	
+0.5	

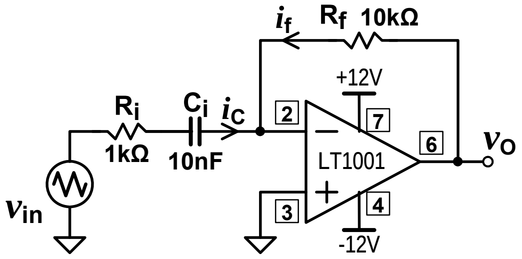
2.3 Set the v_{in} signal source to obtain **1 kHz sine wave** with **4 V**p-p amplitude. Monitor v_{in} and v_O on the oscilloscope and plot the steady state waveforms.



Measure the peak-to-peak output voltage for the following v_{in} frequency settings.

v_{in} sine wave frequency	v_O amplitude (**V**p-p)
500 Hz	
1 kHz	
2 kHz	

3. Build the differentiator circuit given on the right, and set the v_{in} signal source to obtain **500 Hz triangular** wave with **10 V**p-p amplitude. Use a pulse voltage source as v_{in} with the timing parameters, `Trise = 1m`, `Tfall = 1m`, `Ton = 0`, and `Tperiod = 2m` to obtain the triangular waveform.

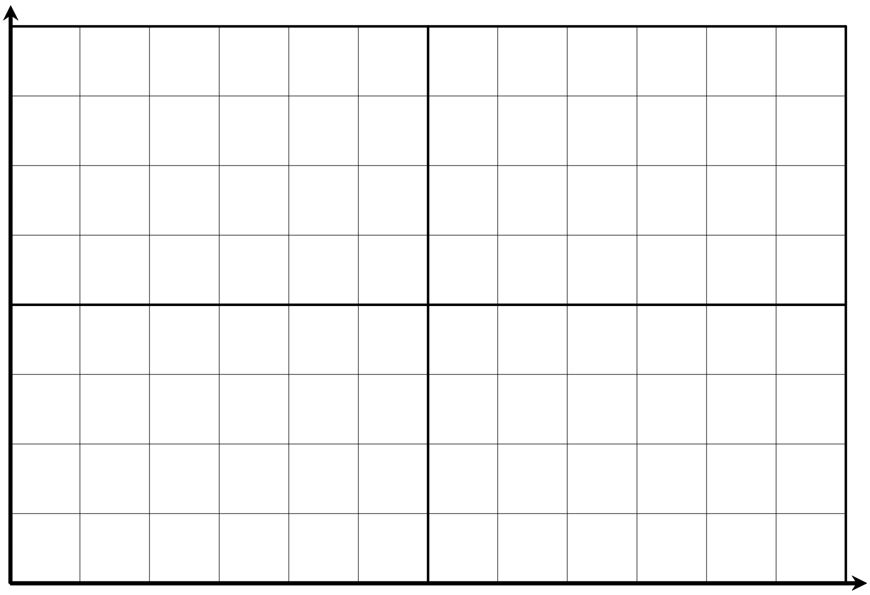


3.1 Display v_{in} and v_O waveforms. Measure the peak-to-peak voltage of the square wave output for the following v_{in} frequency settings.

Note: Ignore short overshoots and undershoots after the rising and falling edges when you measure peak-to-peak voltage of square wave output.

v_{in} triangular wave frequency	v_O amplitude (**V**p-p)
500 Hz	
1 kHz	
2 kHz	

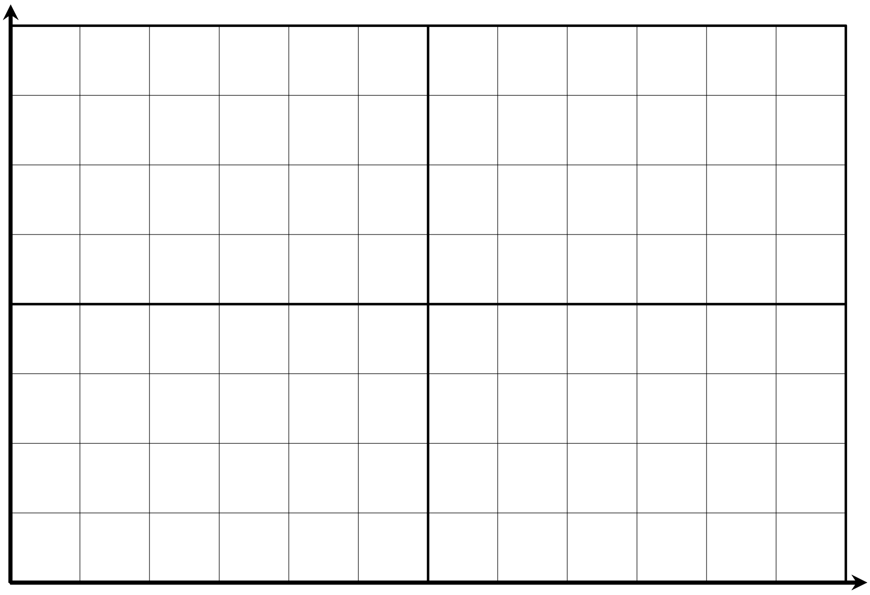
3.2 Set the v_{in} signal source to obtain **1 kHz sine wave** with **2 V**p-p amplitude. Monitor v_{in} and v_O on the oscilloscope and plot the waveforms.



Measure the peak-to-peak output voltage for the following v_{in} frequency settings.

v_{in} sine wave frequency	v_O amplitude (**V**p-p)
500 Hz	
1 kHz	
2 kHz	

3.3 Set the v_{in} signal source to obtain **1 kHz square** wave with **2 V**p-p amplitude. Monitor v_{in} and v_o on the oscilloscope and plot the waveforms..



Questions

Q1.a) Explain the function of **R_f = 10 kΩ** resistor used in procedure step **2**.

b) Explain the function of **R_i = 1 kΩ** resistor used in procedure step **3**.

Q2.a) Derive an expression that gives peak-to-peak output voltage of the integrator in step **2** as a function of square wave amplitude and frequency at the input.

b) Derive an expression that gives DC output voltage of the integrator as a function of the input offset.

c) Derive an expression that gives peak-to-peak output voltage of the integrator as a function of sine wave amplitude and frequency at the input.

d) Compare the results of your calculations in **(a)**, **(b)**, and **(c)** with the experimental results obtained in procedure steps **2.1**, **2.2**, and **2.3**.

Q3.a) Derive an expression that gives peak-to-peak output voltage of the differentiator in step **3** as a function of triangular wave amplitude and frequency at the input.

b) Derive an expression that gives peak-to-peak output voltage of the differentiator as a function of triangular wave amplitude and frequency at the input.

c) Compare the results of your calculations in **(a)** and **(b)**, **(c)** with the experimental results obtained in procedure steps **3.1** and **3.2**.

Q4. List all factors that can affect the peak output voltage in procedure step **3.3** (differentiator with square wave input). Describe the effect of each factor that can be one of the input waveform parameters, circuit components, or opamp supply voltages.

Example: *Peak voltage at v_o increases (or decreases) when rise time of the square wave input increases, because time derivative of v_{in} is ....*