Op-Amp Circuits – Wk 13 (April 14th and April 16th 2020)

LAB 13: SIMULATING Op-Amp circuits : Amplifier, integrator, differentiator, Comparator (Schmitt Triggers)

GOALS
In this lab, we will practice (1) how to implement Op-Amp circuit in LTspice with the OpAmp circuits we are already familiar with -- non-inverting and inverting amplifier. (2) Then we build a few common op-amp circuits that are widely used in a variety of analog circuits.
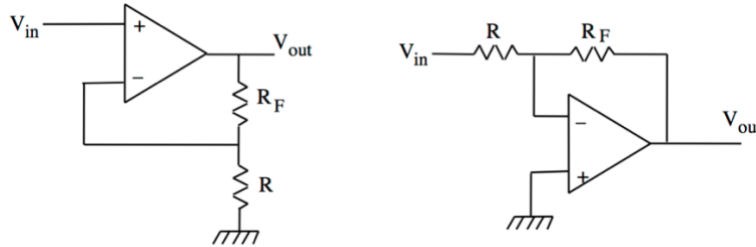

Fig.1 (Left) Non-inverting amplifier (Right) Inverting amplifier, with *negative* feedback

PREP-Lab ACTIVITIES
At this point, you should be *proficient* with the following LTspice set-up. Please review Lab 11 and 12 manuals and supplemental materials before proceeding, if needed.
   (1) Transient and AC analysis
   (2) Basic circuits building skills such as adding components, and grounds and wiring them the voltage sources for DC and AC in various wave form.

LAB ACTIVITIES
Step 1: Building inverting amplifier in LTspice:
(a) Open new file and go to component/opamp. Choose **LT1001 (or universal op-amp)** for now, the simplest dual supply op-amp. Note that if you choose ideal opamp but this will require lib.opamp.sub spice directive.
(b) you will need three voltage sources – two for powering op-amp (+/- 15 V as we did in lab 4) and one for Vin (AC source) and 2 resistor that will determine the gain of this amplfier.
(c) make sure add ground properly for all three voltage sources.
(d) Now connect wires and give the resistor value, like R1 = 1K ohm and R2 = 5 kohm.
(e) What is the gain and f_{3dB} of this amplifier? Change the values of feedback resistor (R2) to change gain. Does f3dB changing accordingly ?
(f) Run the AC analysis in reasonable range of frequencies, e.g. 10 Hz < f < 10 MHz. Find out the unity gain bandwidth (f_T) of this op-amp. Please include your AC analysis in your write-up.
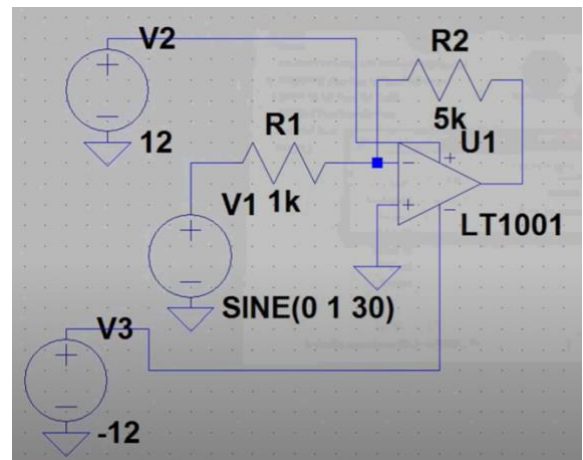

Fig. 2 Inverting amplifier. Note that +/- 12V was used to power op-amp shown in here. Do not forget adding the "grounds" in your circuit.

Step 2: Building non-inverting amplifier
Follow the same procedure **Step1 (a)- (f)** to build non-inverting amplifier with the same gain. Run AC analysis to check the 3dB frequency.

Step 3: Integrator and differentiator with opamp

(a) Fig.3 shows the integrator circuit we built in Lab 6. Use **R = 1 kohm *and* C = 10 nF** to build integrator. What is the characteristic frequency, fc = 1/ (2πτ), of this circuit?   Pick one or two frequencies of square wave and triangular at which the circuit works as integrator at the ***transient analysis***.   Add very large Bleeder resistor (R_B > 20 meg ohm) parallel to the feedback capacitor. Does it make any difference in your circuit?

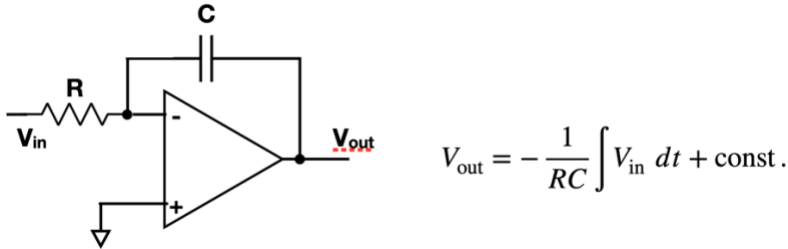$$V_{out} = - \frac{1}{RC} \int V_{in}\, dt + \text{const}.$$

Fig.3 Integrator and its equation

** There may be a problem with a ringing problem (high frequency oscillations) in V_{out} signal. In that case, you can either try to switch your opamp to "ideal op-amp"(this requires extra sub-directory on your circuit) or "universal opamp", with higher slew rate.

(b) Now switch R and C above circuit to act as differentiator. Using the same R and C value, check the differentiating function of this circuit with the transient analysis using a proper frequency of square and triangular wave forms. How does it behave when frequency is much higher than f_c, (e.g. f > 10f_c) .

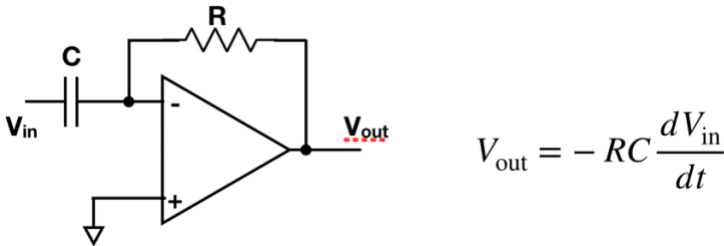$$V_{out} = - RC \frac{dV_{in}}{dt}$$

Fig.4 Differentiator and its equation

(c) Now build the following circuit shown in Fig. 5 – which most commonly used for differentiator with more frequency-limited. Which combination of R and C determines the cutoff frequency of this circuit in Fig. 5? Explain briefly your reasoning or observations. If V_{out} exhibits high frequency oscillation (rining), try different values for the components e.g. R_1=10 Kohm, C_1= 4 nF, R_2 = 10 kohm and C_2=100 pF)
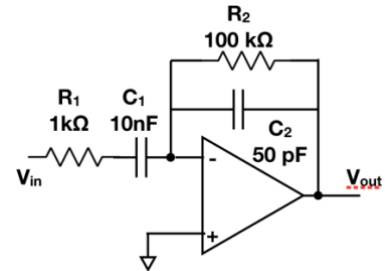

Fig. 5 Differentiator with smaller cutoff frequency.

Step 4: Comparators and positive feedback

Recall the basic operation principle of op-amplifer is a differential amiplifier, i.e. $V_{out} = A_0(V_+ - V_-)$, where A_0, open loop gain and is very large number (> 10^{4-5}).   And if |Vout| is larger than the biased DC voltage (We have been setting V_{dc} = +/-15 V for positive and negative).

When |V_{out}|> V_{dc} , the V_{out} is ***saturated*** to one of V_{dc} values.   For example, two unknown signals come into V- and V+ and if V+ > V- , the output voltage would be railed to $V_{dc(+bias)}$ value. Otherwise, it would be $V_{dc(-bias)}$ value -- a simple comparison is made!
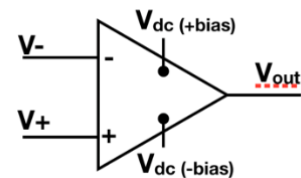

Fig. 6 Basic differential amplifier

(1) Because there is no negative feedback in the comparator circuit, the *golden rule #1* ("The voltage different between two inputs, V+ and V-, is virtually zero") is **NOT VALID!**

(2) Again, due to absence of negative feedback, we cannot always assume the characteristic high input impedance of op-amp circuit.

(3) Op-amps do not require +/-15 V symmetric DC supplies. They can be operated from split supplies of lower voltages or from unsymmetrical supply voltage (e.g. +12 V and -3 V). From now on, we will set Vdc(-bias) = 0 (i.e. ground) and Vdc(+bias) = 5 V.   In this case, V_{out} would be either +5 V or 0 V.

Now consider an input signal   as shown in Fig. 7 upper panel. The straight line indicates the triggering (reference) point.

When $V_{in} > V_{ref}$, V_{out} would be 5 V, and when $V_{in} < V_{ref}$, V_{out} = 0 V. Often, due to the noisiness of the input signal (Fig. 7 upper panel), the output makes several transitions as the input passes through the reference point. In order to mitigate this, we can set a range of threshold (Fig. 7 lower panel), where the transition would not be made until the size of input signal goes up/down beyond threshold. This will make the circuit performance more stable and we will practice this in the following steps.
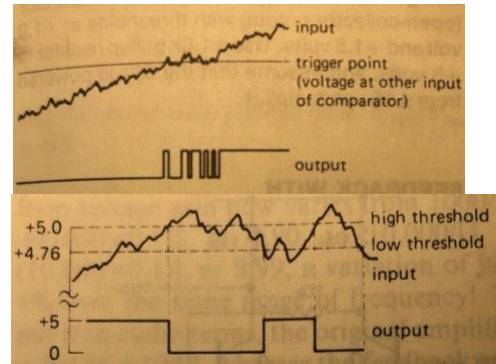

Fig. 7 (upper) Schematics of how comparator work with noisy input. (lower) Instead, providing a threshold range, within which the output would stay where it was, making circuit performance more stable.

(a) Now, Let's build the following comparator circuit (Schmitt trigger) shown in Fig. 8.
What is the voltage at V_{ref} point?   (Hint: Voltage divider of R_1 and R_2). Note that by changing R_1 and R_2 value to change V_{ref} as you like.

(b) In order to simulate a "noisy" input signal, use a triangular wave with (V_{max} = 6.5 V and V_{min} = 0 V) frequency of 1kHz. What would the output look like if you run a transient analysis with STOP Time 2 ms ?
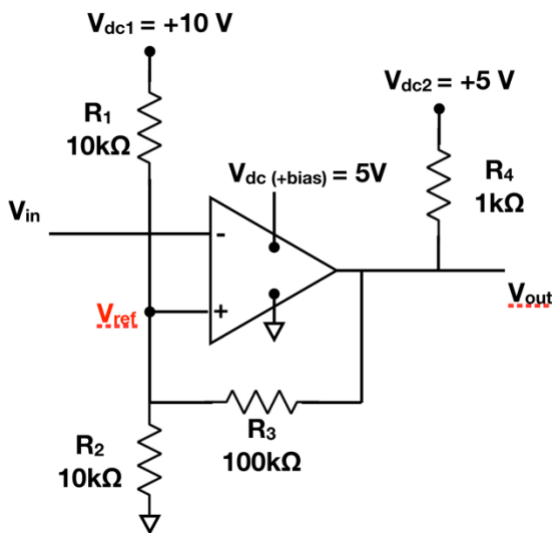

Fig 8. Schmitt trigger with *positive* feedback resistor

(c) Now remove the positive feedback resistor R3. Run the same transient analysis. Is it different from what you find in (b) ? How does it different?

(d) Putting back the feedback resistor to the circuit as shown in Fig. 8, change the R_3 to 10Kohm and 1 meg ohm. How does the threshold change for each case? (Note that R_4 is to ensure the full swing of V_{out} between 0 and 5 V.   In real circuit design, you may wish to scale all resistor values in order to keep the output current and impedance levels within a reasonable range.)

Appendix: Number convention of LTspice (Modified from Wikipedia)

SPICE Suffix[26]	Metric Name	English Name	Power of 10	Numeric Value	Notes and Common Mistakes
u or μ	micro	Millionth	10^{-6}	0.000001	Older SPICE software does not support the μ(Mu) character
T	tera	Trillion	10^{12}	1000000000000	
p	pico	Trillionth	10^{-12}	0.000000000001	
n	nano	Billionth	10^{-9}	0.000000001	
mil	thou		25.4×10^{-6}	0.0000254	mil is a thousandth of an inch(0.001") which is 25.4 μm[26]
MEG	mega	Million	10^{6}	1000000	Wrong use of m/meg/mil are common mistakes in all SPICE programs
m	milli	Thousandth	10^{-3}	0.001	"1m" & "1M" doesn't mean "1megaohm, instead "1MEG" is correct[1]
K	kilo	Thousand	10^{3}	1000	
G	giga	Billion	10^{9}	1000000000	

· The suffix (left column) is case insensitive.[1] For example, 1MEG / 1meg / 1Meg represents 1000000; 1k / 1K represents 1000.

· Any appended text after the suffix (left column) is ignored.[1] For example, 2MegHz / 2MegaOhm represents 2000000; 3mV / 3mOhm represents 0.003.

· In LTspice, any suffix (left column) can replace the decimal point of a real number, a common format for printed schematics.[1] For example, 4K7 represents 4700, 1u8 represents 0.0000018.

[1] LTspice - General Conventions". *Ltwiki*. Archived from the original on December 5, 2018.