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Experiment- 5
Operational Amplifier

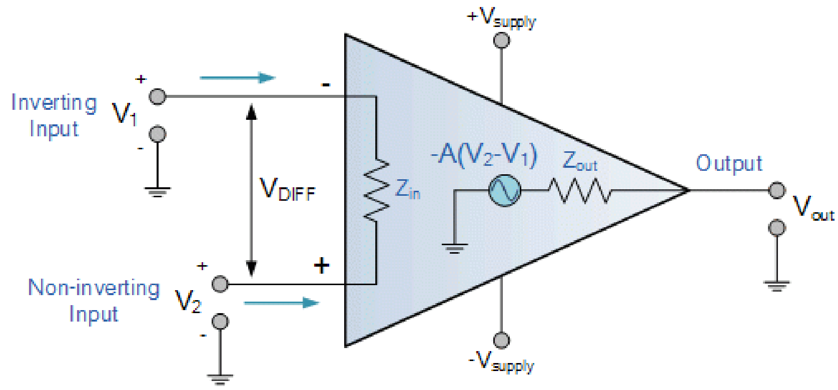
Objectives
- Measurement of DC gain of the OP-AMP
- Observe OP-AMP as Non-Inverting Amplifier
- Observe OP-AMP as Voltage Follower
- Observe OP-AMP as an Adder
- Observe OP-AMP with simultaneous inputs at inverting and noninverting terminals
- Observe OP-AMP as an Integrator
- Observe OP-AMP as Differentiator

Apparatus

S. No.	Apparatus	Range	Type	Quantity
1)	Resistor	1kΩ-100kΩ	-	3
2)	Capacitor	0.1μF - 1μF	-	2
3)	Op-Amp	-	OP07	1
4)	Voltage Source	1mV-12V	AC - i)Square Wave ii)Sine Wave DC	3

Theory
An Operational Amplifier, or op-amp for short, is fundamentally a voltage amplifying device designed to be used with external feedback components such as resistors and capacitors between its output and input terminals. These feedback components determine the resulting function or “operation” of the amplifier and by virtue of the different feedback configurations whether resistive, capacitive or both, the amplifier can perform a variety of different operations, giving rise to its name of “Operational Amplifier”.
An Operational Amplifier is basically a three-terminal device which consists of two high impedance inputs. One of the inputs is called the Inverting Input, marked with a negative or “minus” sign, (–). The other input is called the Non-inverting Input, marked with a positive or “plus” sign (+).Op-Amp shows some properties that make it an ideal amplifier, its open loop gain and input impedance is infinite (i.e.,practically very high), Output impedance and offset

voltage is zero(i.e.,practically very low) and bandwidth is infinite(i.e.,practically limited to frequency where its gain become unity).

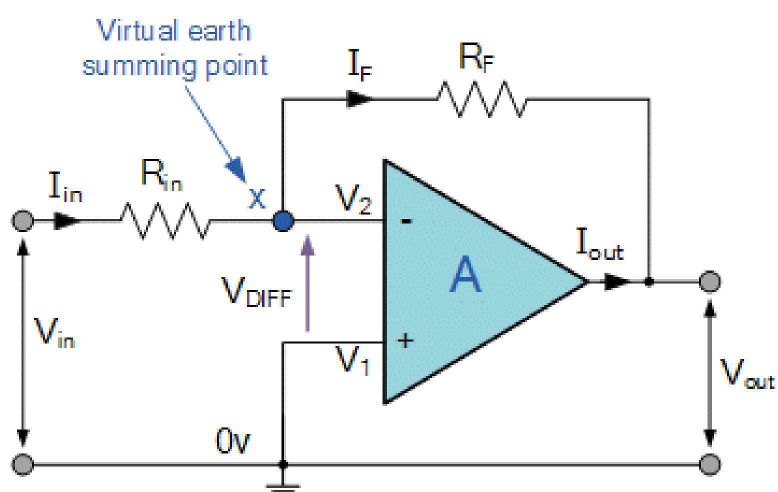


Inverting Op-Amp

An inverting amplifier (also known as an inverting operational amplifier or an inverting op-amp) is a type of operational amplifier circuit which produces an output which is out of phase with respect to its input by 180.

This means that if the input pulse is positive, then the output pulse will be negative and vice versa. The figure below shows an inverting operational amplifier built by using an op-amp and two resistors.

Here we apply the input signal to the inverting terminal of the op-amp via the resistor Ri. We connect the non-inverting terminal to ground. Further, we provide the feedback necessary to stabilize the circuit, and hence to control the output, through a feedback resistor Rf.



This indicates that the voltage gain of the inverting amplifier is decided by the ratio of the feedback resistor to the input resistor with the minus sign indicating the phase-reversal. Further, it is to be noted that the input impedance of the inverting amplifier is nothing but Ri.

Inverting amplifiers exhibit excellent linear characteristics which make them ideal as DC amplifiers. Moreover, they are often used to convert input current to the output voltage in the form of Transresistance or Transimpedance Amplifiers. Further, these can also be used in audio mixers when used in the form of Summing Amplifiers.

$$I = \frac{(V_{in} - V_{out})}{(R_{in} + R_F)}$$

or,

$$I = \frac{V_{in} - V_2}{R_{in}}$$

or,

$$I = \frac{V_2 - V_{out}}{R_F}$$

$$I = \frac{V_{in}}{R_{in}} - \frac{V_2}{R_{in}} = \frac{V_2}{R_F} - \frac{V_{out}}{R_F}$$

So,

$$\frac{V_{in}}{R_{in}} = V2 \times \left(\frac{1}{R_{in}} + \frac{1}{R}\right) - \frac{V_{out}}{R_F}$$

As $V_2 = 0$

$$I = \frac{V_{in}}{R_{in}} = -\frac{V_{out}}{R_F}$$

The close loop gain (A_{cl}) is given by,

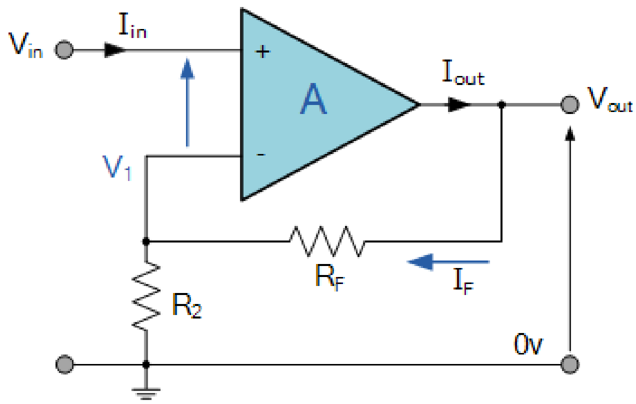
$$A_{cl} = \frac{V_{out}}{V_{in}} = -\frac{R_F}{R_{in}}$$

Thus output voltage is given by,

$$V_{out} = -\frac{R_F}{R_{in}} \times V_{in}$$

Non-Inverting Op Amp:

A non inverting operational amplifier or non inverting op amp uses op amp as main element. The op amp has two input terminals (pins). One is inverting denoted with minus sign (-), and other is non-inverting denoted with a positive sign (+). When we apply any signal to the non – inverting input of, it does not change its polarity when it gets amplified at the output terminal. So, in that case, the gain of the amplifier is always positive.



Potential Difference V1 can be written as,

$$V_1 = \frac{R_2}{R_2 + R_F} \times V_{out} \;:$$

In ideal condition, $V_1 = V_{in}$

So,

$$V_{in} = \frac{R_2}{R_2 + R_F} \times V_{out}$$

WKT, Gain $A_{cl} = \frac{V_{out}}{V_{in}}$

$$\therefore A_{cl} = 1 + \frac{R_F}{R_2}$$

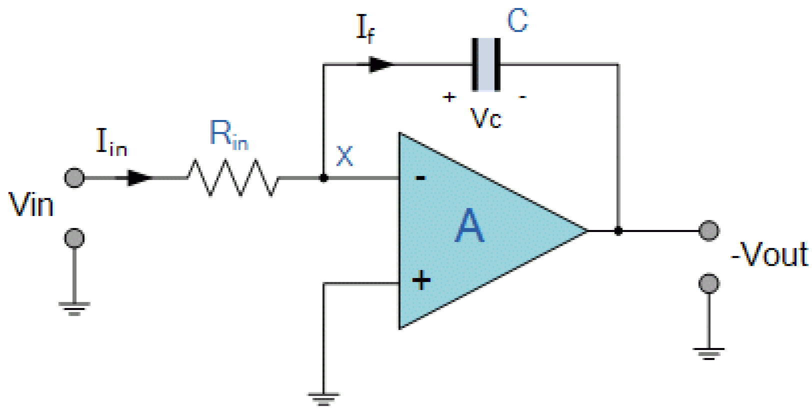
Thus, output voltage is

$$V_{out} = \left(1 + \frac{R_F}{R_2}\right) V_{in}$$

In this configuration of Op-amp the input signal is directly fed to the non inverting terminal resulting in a positive gain and output voltage in phase with input as compared to inverting Op-amp where the gain is negative and output voltage is out of phase with input , and to stabilize the circuit a negative feedback is applied through a resistor(Rf) and the inverting terminal is grounded with an input resistor (R2).This inverting Op-Amp like layout the at inverting terminal creates a virtual ground at the summing point make the Rf and R2 a potential divider across inverting terminal, Hence determines the gain of the circuit.

Integrating Op Amp:

An integrator is an op amp circuit, whose output is proportional to the integral of input signal. An integrator is basically an inverting amplifier where we replace feedback resistor with a capacitor of suitable value



It is a circuit designed with Op-Amp in such a way that it performs the mathematical Integration operation, its output is proportional to the amplitude and time duration of the input applied. The integrator circuit layout is the same as an inverting amplifier but the feedback resistor is replaced by a capacitor which makes the circuit frequency dependent. In this case the circuit is derived by the time duration of input applied which results in the charging and discharging of the capacitor.

Initially when the voltage is applied to integrator the uncharged capacitor allows maximum current to pass through it and no current flows through the Op-Amp due to the presence of virtual ground, the capacitor starts to charge at the rate of RC time constant and its impedance starts to increase with time and a potential difference is developed across the capacitor resulting in charging current to decrease.

This results in the ratio of capacitor's impedance and input resistance increasing causing a linearly increasing ramp output voltage that continues to increase until the capacitor becomes fully charged.

The output voltage is potential difference across capacitor,

$$V_c = \frac{Q}{c}$$

$$V_c = V_x - V_{out} = -V_{out}$$

Thus, $-\frac{dV_{out}}{dt} = \frac{1}{c}\frac{dQ}{dt}$

And input current can be written as,

$$I_{in} = \frac{V_{in}}{R_{in}}$$

The current through capacitor (I_f) can be written as,

$$I_{in} = I_f = \frac{V_{in}}{R_{in}} = C \times \frac{dV_{out}}{dt}$$

Thus,

$$\frac{V_{in}}{dV_{out}} \times \frac{dt}{R_{in} \times C} = 1$$

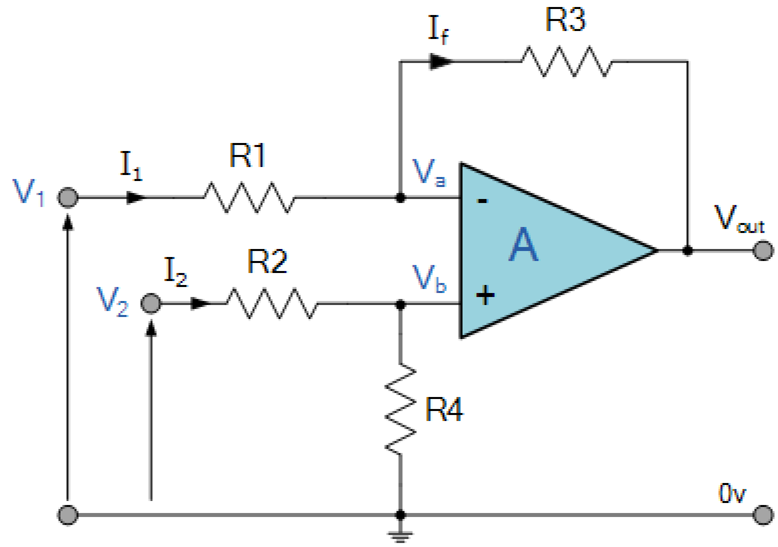
$$V_{out} = -\frac{1}{R_{in} \times C} \int V_{in} \cdot dt$$

$$\therefore V_{out} = -\frac{1}{j\omega R_{in} C} V_{in}$$

The -ve sign indicates 180° phase shift

Differentiator Op-Amp:

Differentiator is an op amp based circuit, whose output signal is proportional to differentiation of input signal.
An op amp differentiator is basically an inverting amplifier with a capacitor of suitable value at its input terminal. The figure below shows the basic circuit diagram of an op amp differentiator.



Node Voltage $V_x = 0$,

$$I_{in} = I_f = -\frac{V_{out}}{R_f}$$

The charge across capacitor is,

$$Q = c \times V_{in}$$

The rate of change of charge is,

$$\frac{dQ}{dt} = c \times \frac{dV_{in}}{dt}$$

$$I_f = \frac{dQ}{dt} = c \times \frac{dV_{in}}{dt} = I_{in}$$

Thus,

$$-\frac{V_{out}}{R_f} = c \times \frac{dV_{in}}{dt}$$

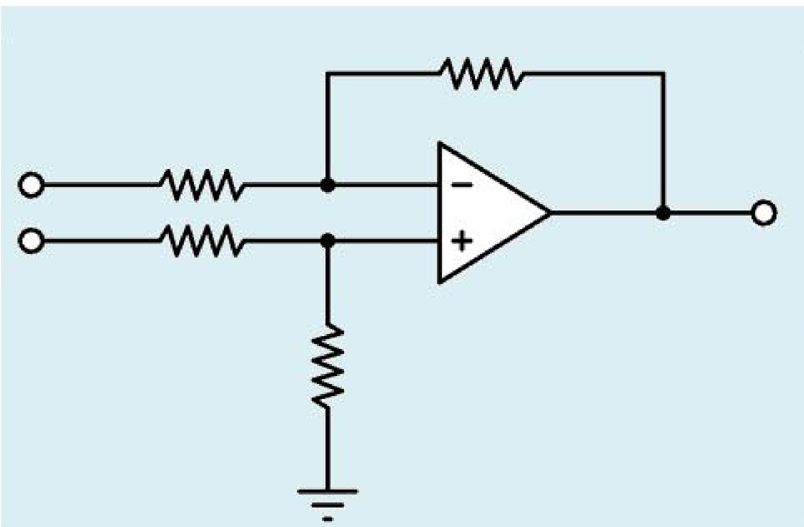
$$\therefore \quad V_{out} = -R_f \times c \times \frac{dV_{in}}{dt}$$

In the differentiator circuit the input is connected to the the inverting output of the Op-Amp through a capacitor(C) and a negative feedback is provided to the inverting input terminal through a resistor(Rf), which is same as an integrator circuit with feedback capacitor and input resistor being replaced with each other. Here the circuit performs a mathematical differentiation operation, and the output is the first derivative of the input signal, 180' out of phase and amplified with a factor Rf*C. The capacitor on the input allows only the AC component and restricts the DC, at low frequency the reactance of the capacitor is very high causing a low gain and high frequency vice versa but at high frequency the circuit becomes unstable.

Superposition

We have till now considered only the circuits that accept signals at only one of the two output input terminals of the op-amps. An op-amp circuit can provide simultaneous inputs at the inverting and noninverting terminals. Using the superposition theorem which in this case implies that if Vout is the response due to V1 acting alone i.e. with V2 being grounded. Then response due to both inputs is added.

Differential Amplifier

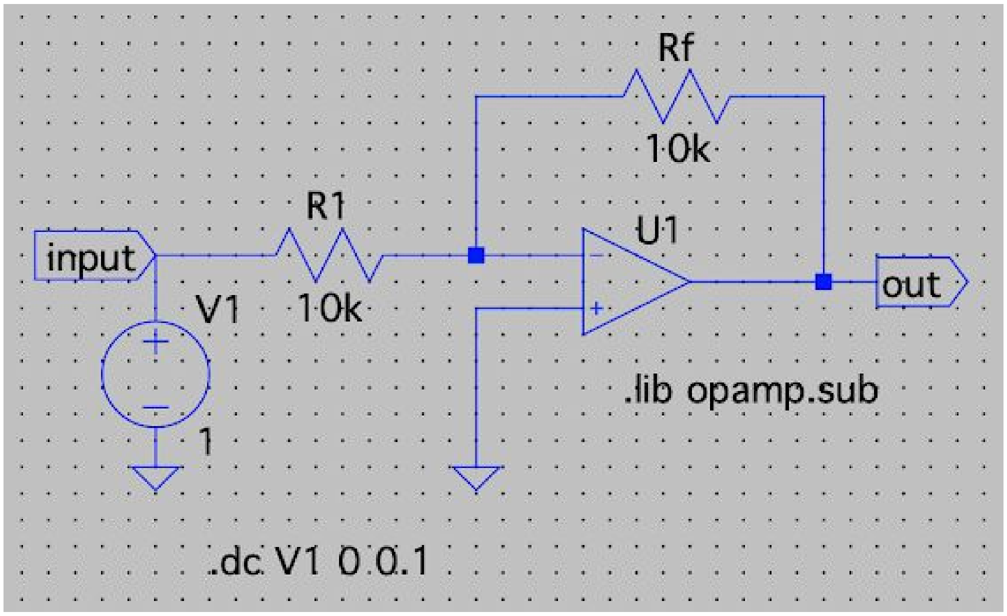


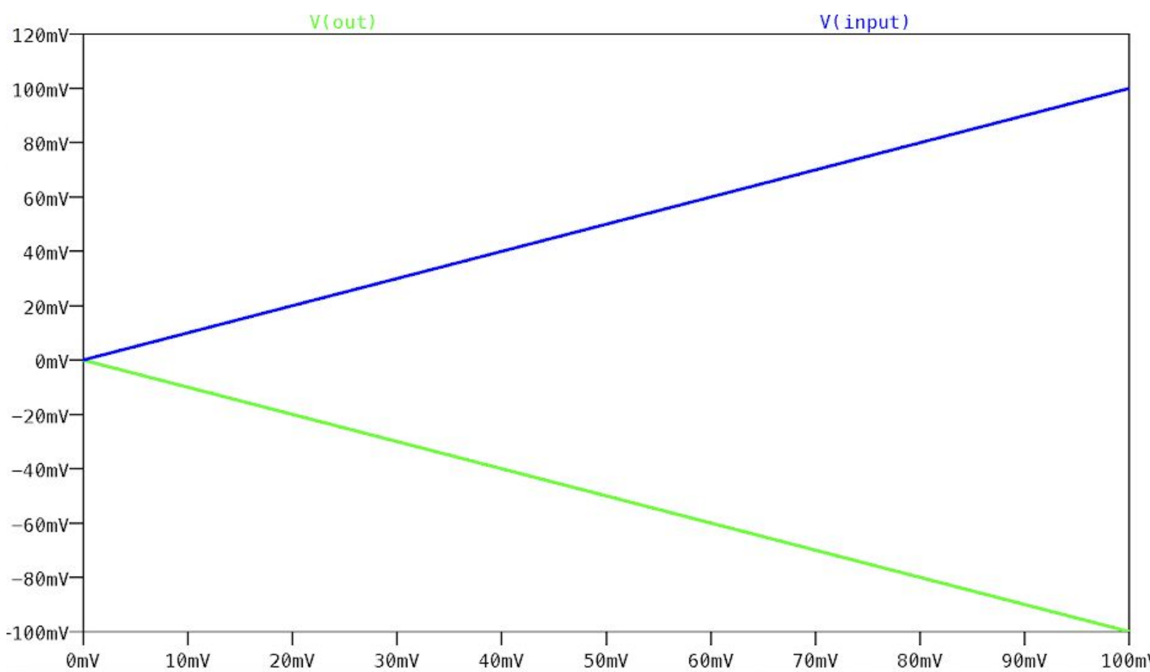
Operational Amplifier is internally a Differential Amplifier with features like High Input Impedance, Low Output Impedance etc. The differential pair or differential amplifier configuration is a most widely used building block in analogue integrated-circuit design. It is the input stage of every operational amplifier, virtually. A difference amplifier or differential amplifier amplifies the difference between the two input signals. An operational amplifier is a difference amplifier; it has an inverting input and a non-inverting input. But the open loop voltage gain of an operational amplifier is too high (ideally infinite), to be used without a feedback connection. The response due to both inputs V1 and V2 acting simultaneously is

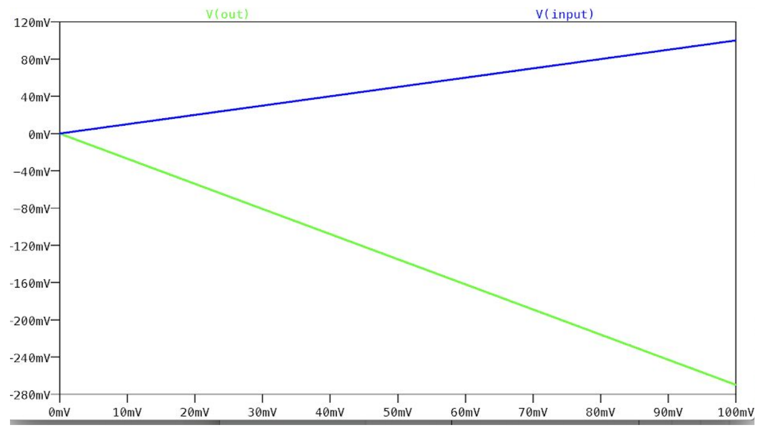
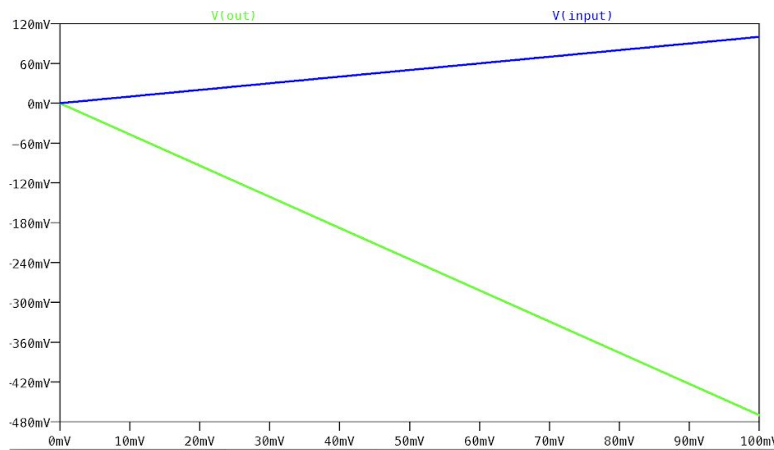
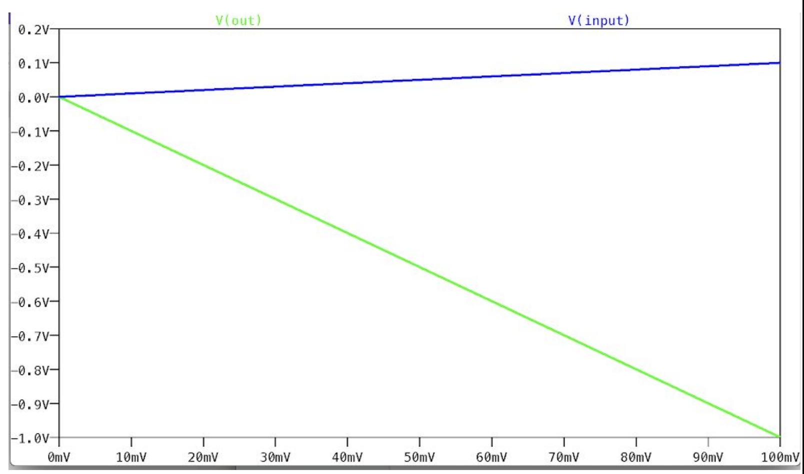
$$Vout \propto Vi1 + Vi2$$

Circuit Diagram And Graphs:

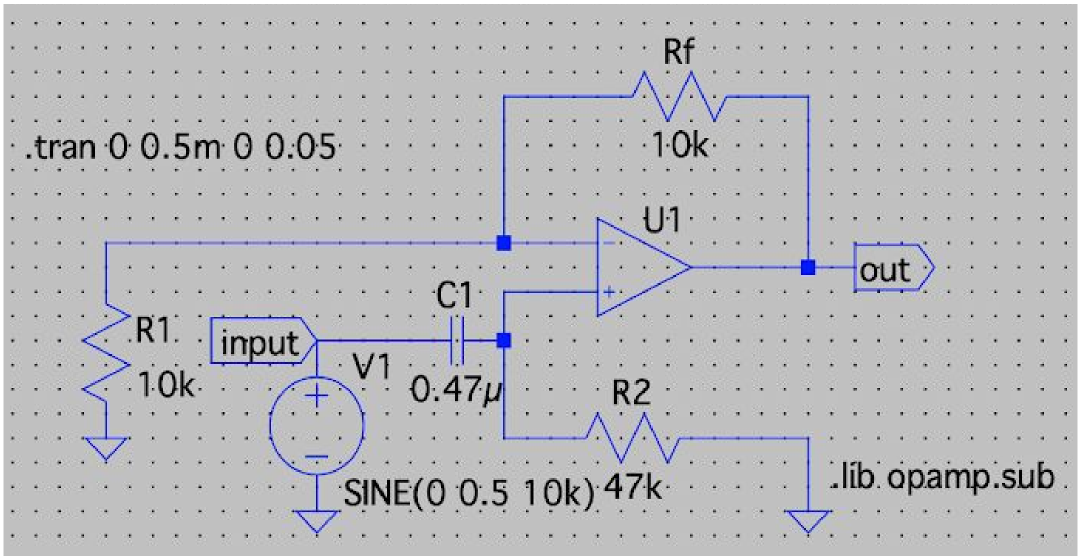
1) Inverting Op-Amp

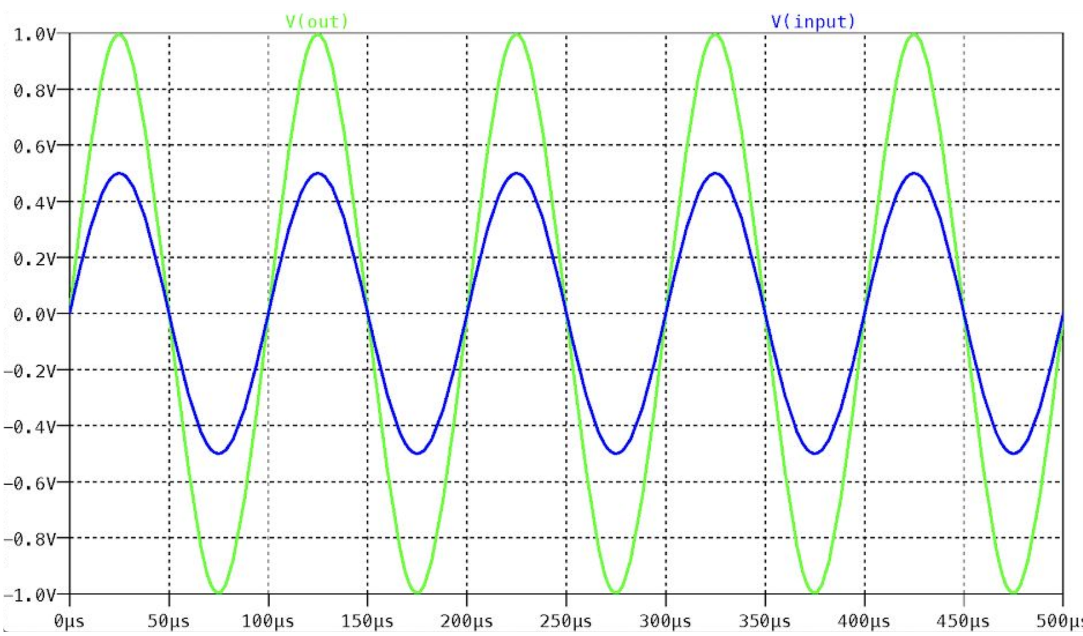


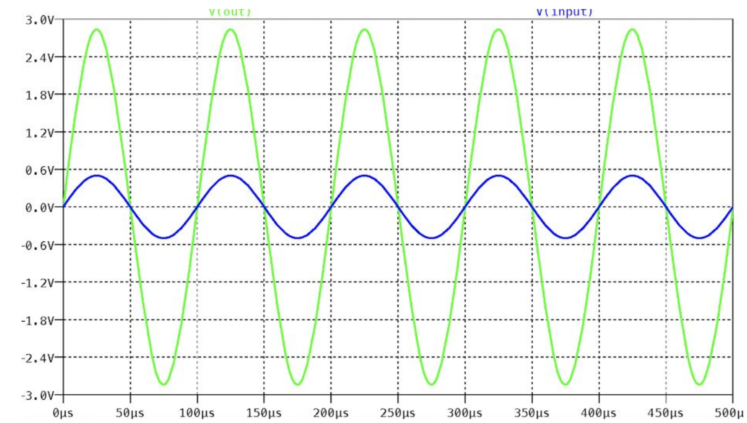
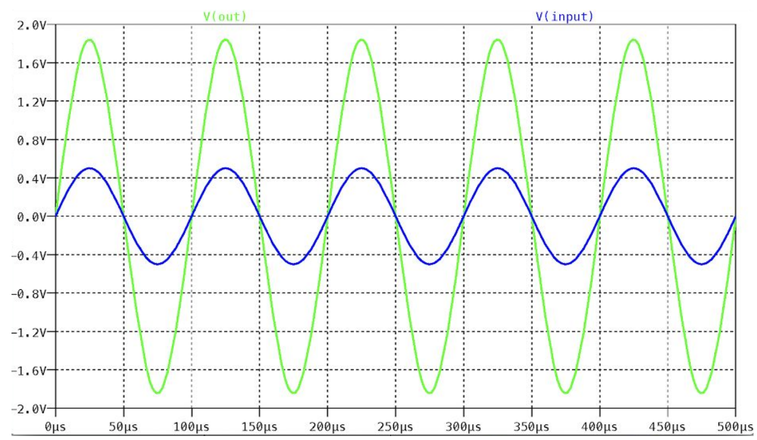
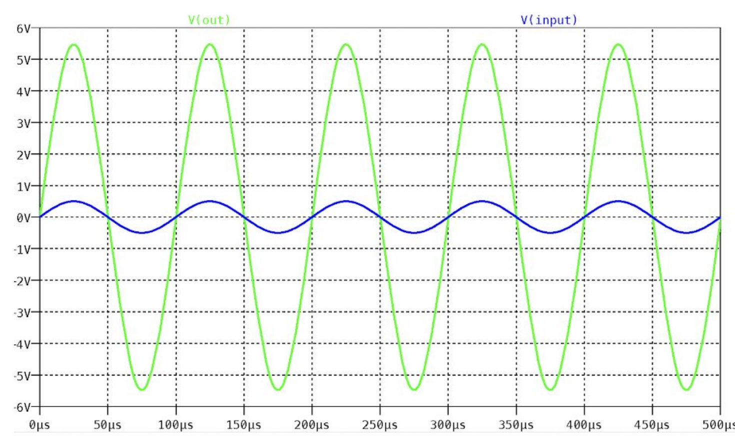


Rf value	Input and Output Curves
Values of Rf = 27 kΩ	
Values of Rf = 47 kΩ	
Value of Rf = 100 kΩ	

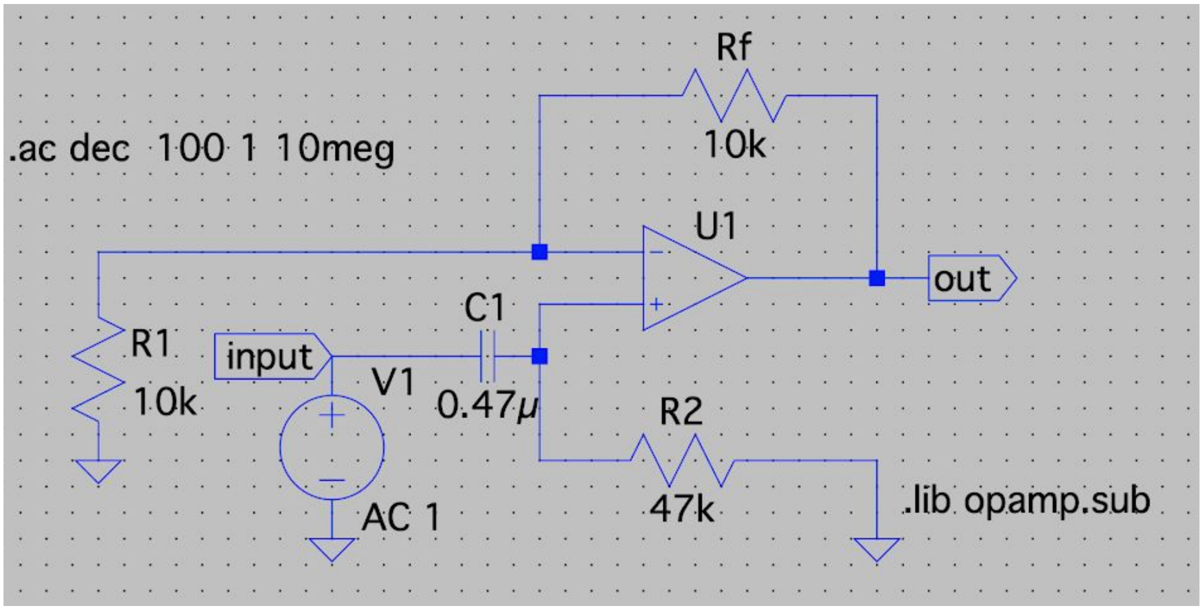
2) <u>Non - Inverting Op Amp</u>

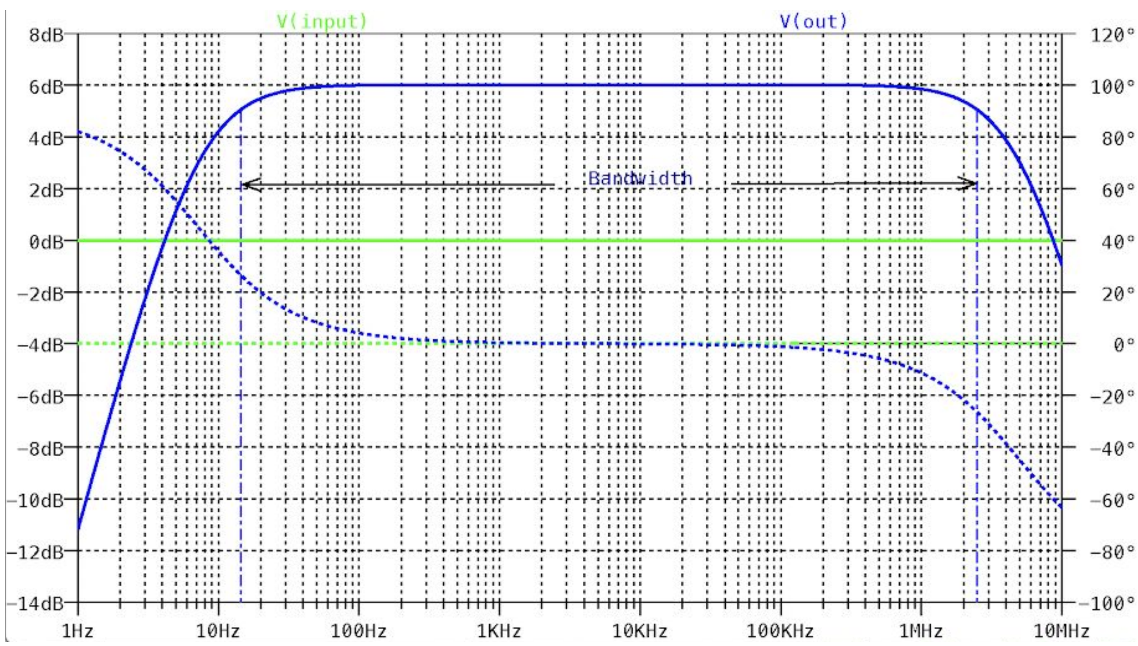


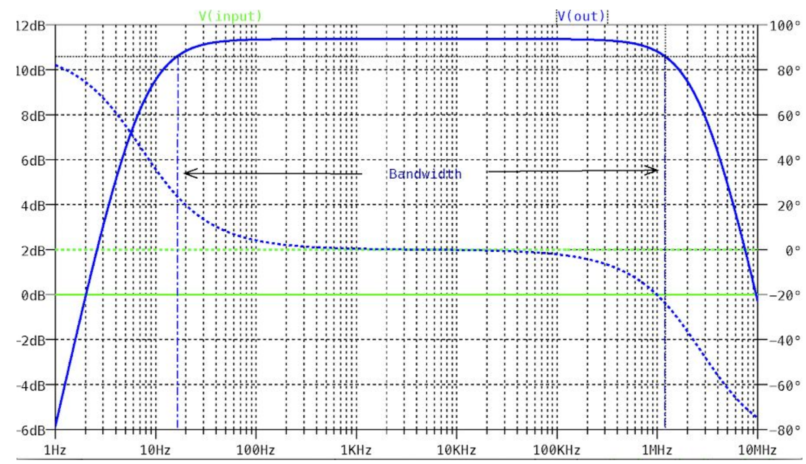
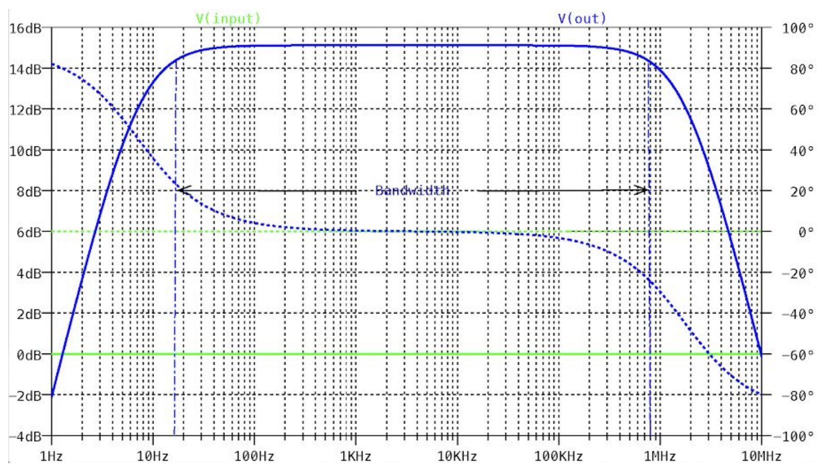
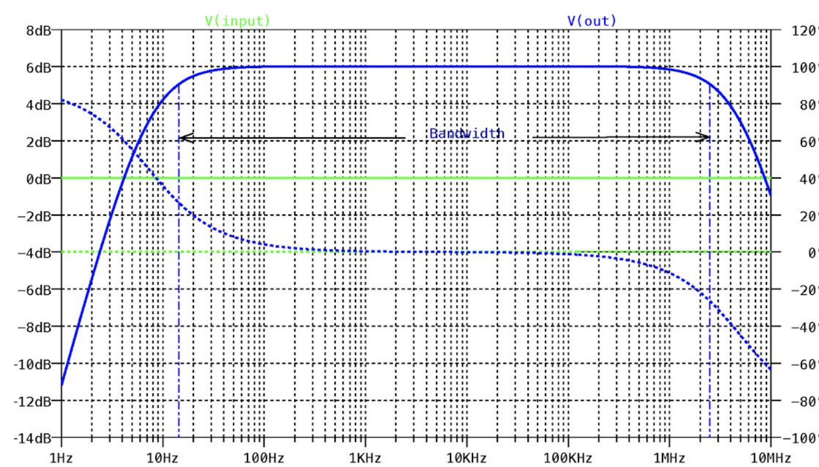


Rf value	Input and Output Curves
Values of Rf = 27 kΩ	
Values of Rf = 47 kΩ	
Value of Rf = 100 kΩ	

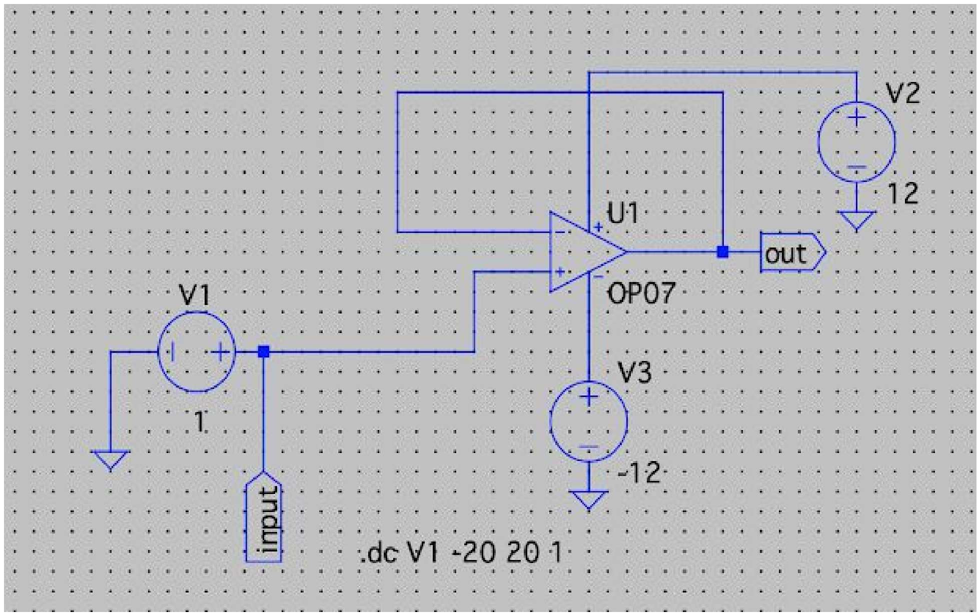
ii) Frequency Response

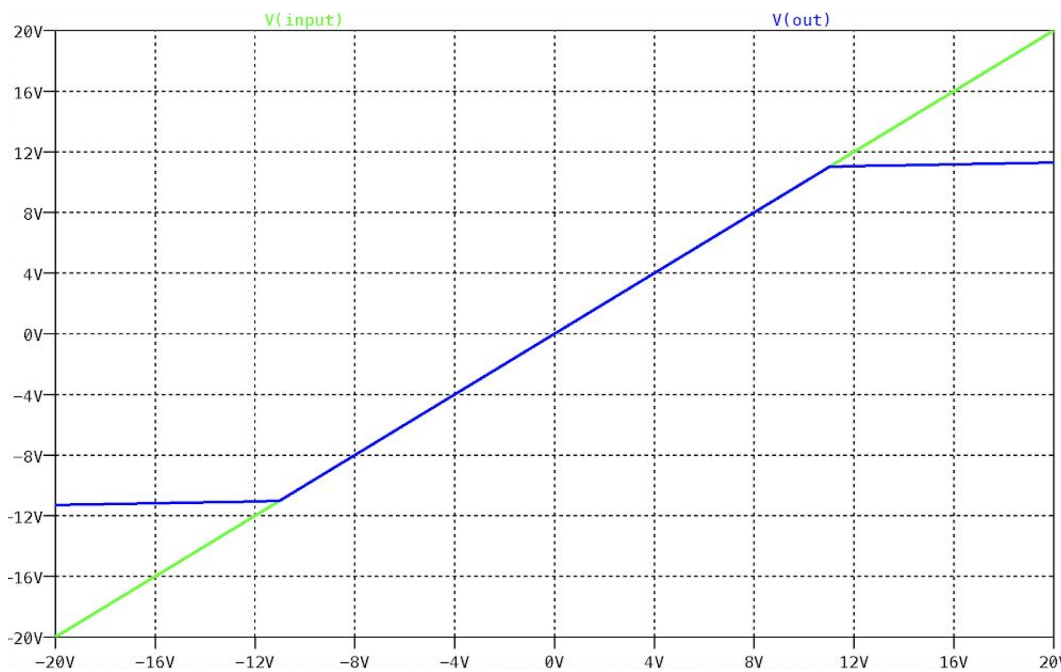




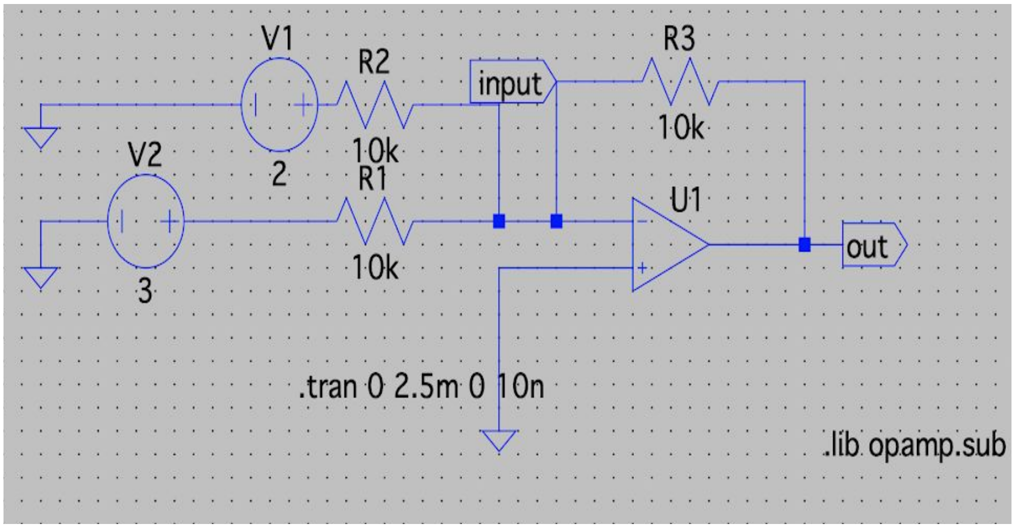
Rf value	Input and Output Curves
Values of Rf = 27 kΩ	
Values of Rf = 47 kΩ	
Value of Rf = 100 kΩ	

3) Voltage Follower

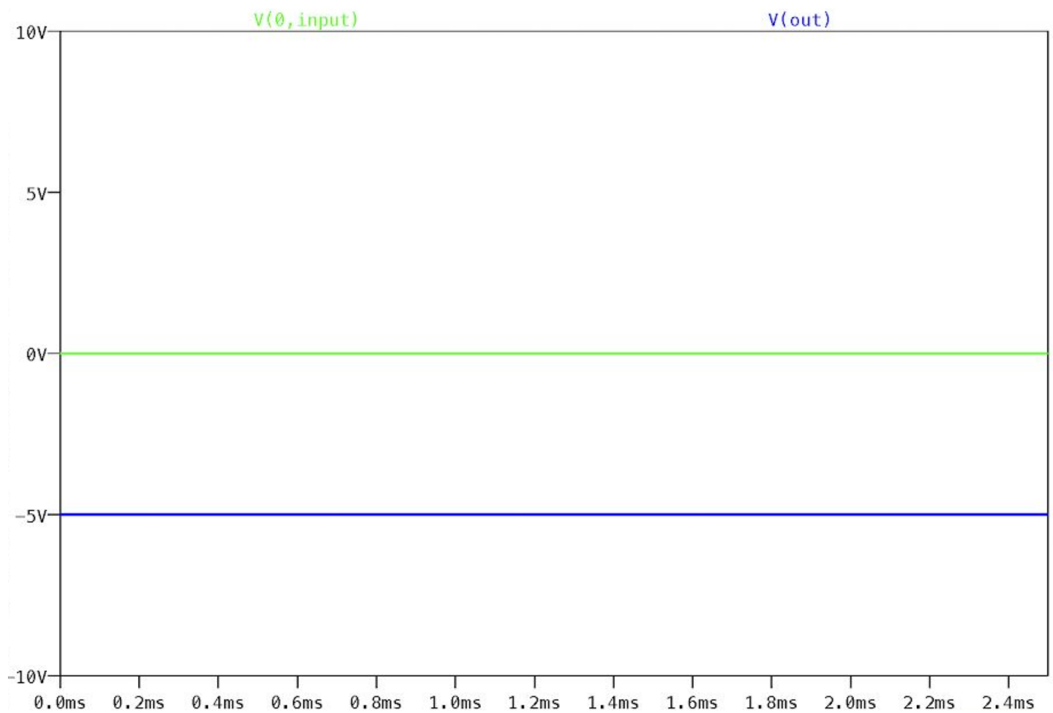




4) <u>Adder</u>

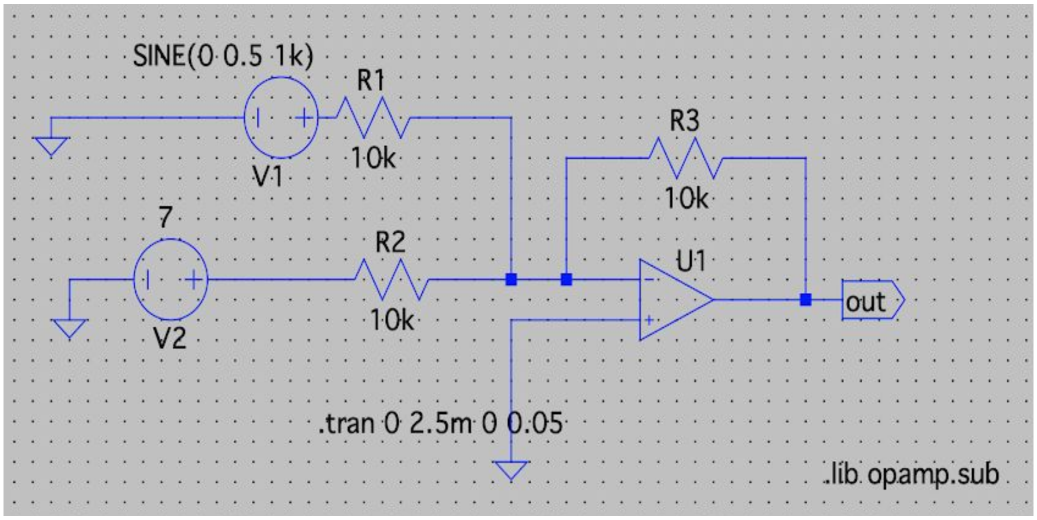


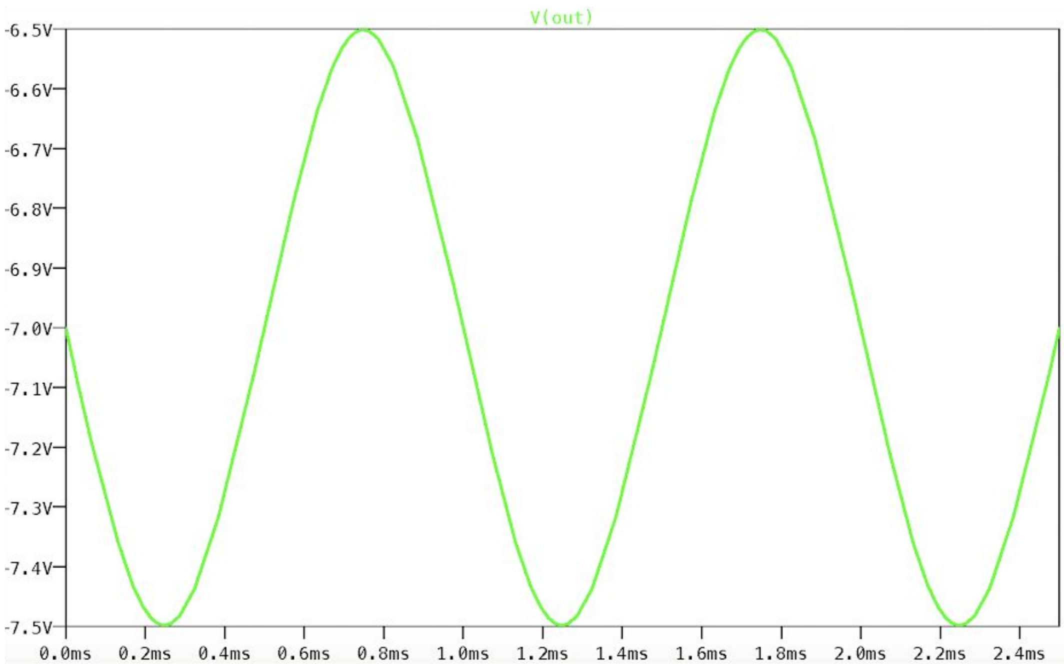
V1
R2
input
R3
10k
V2
2
10k
R1
U1
out
3
10k
.tran 0 2.5m 0 10n
.lib opamp.sub



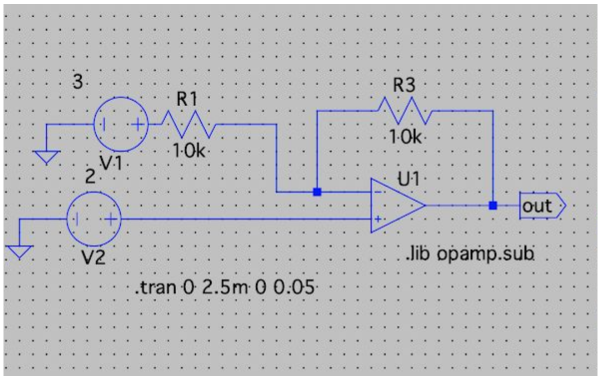
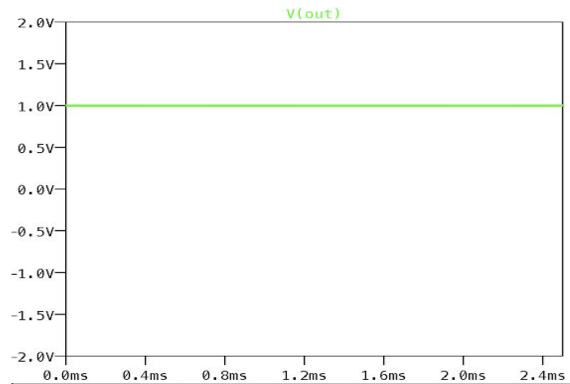
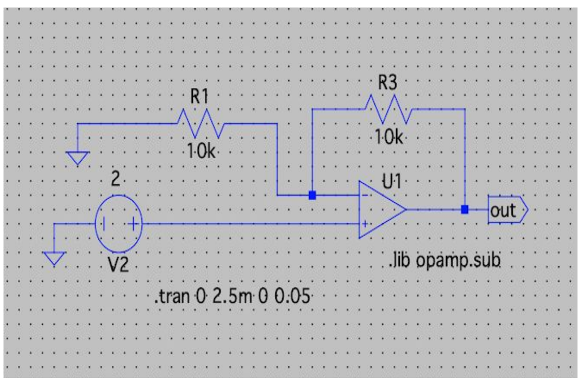
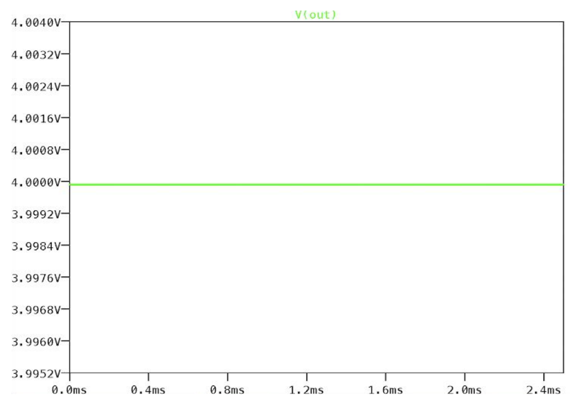
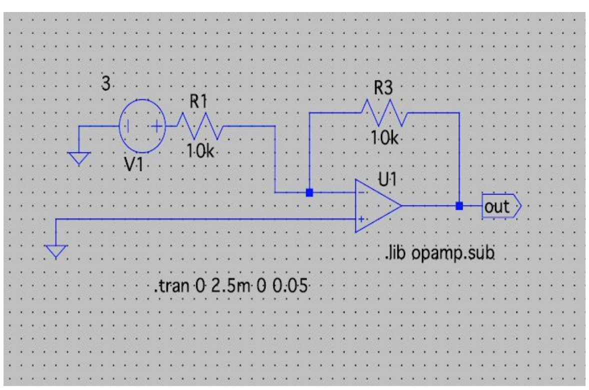
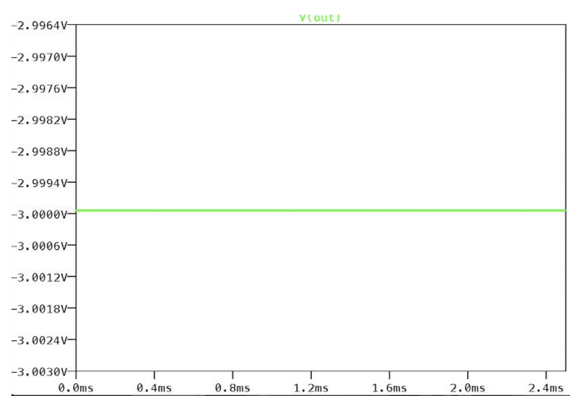
V(0,input)
V(out)
10V
5V
0V
-5V
-10V
0.0ms
0.2ms
0.4ms
0.6ms
0.8ms
1.0ms
1.2ms
1.4ms
1.6ms
1.8ms
2.0ms
2.2ms
2.4ms

ii) Summing Amplifier





5) <u>Superposition</u>

Rf = 10kΩ	Graphs
	
	
	

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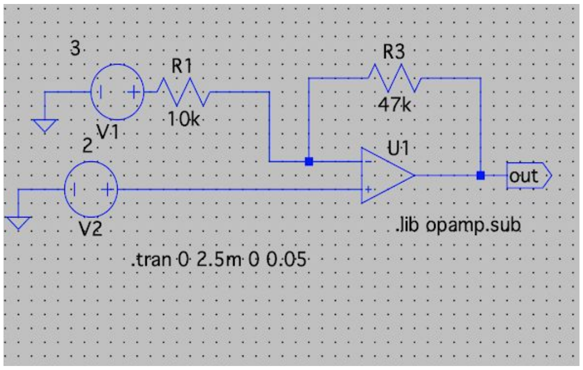
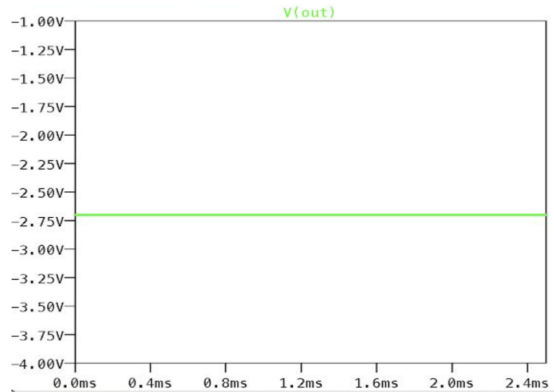
<tr><th>Rf = 47kΩ</th><th>Graphs</th></tr>
<tr><td>
</td><td>
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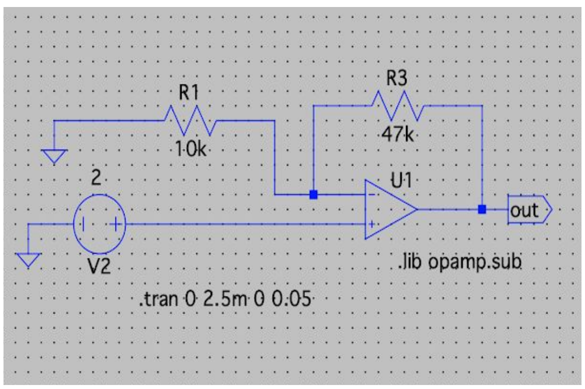
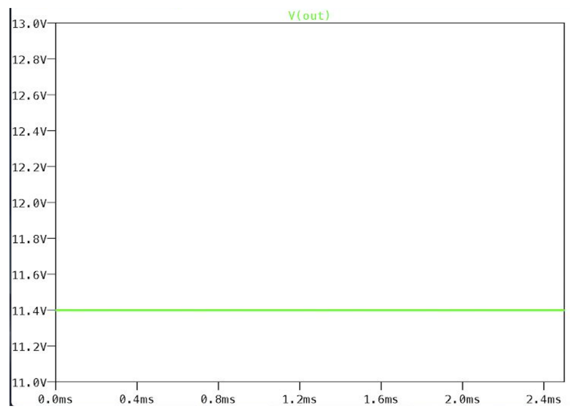
<tr><td>
</td><td>
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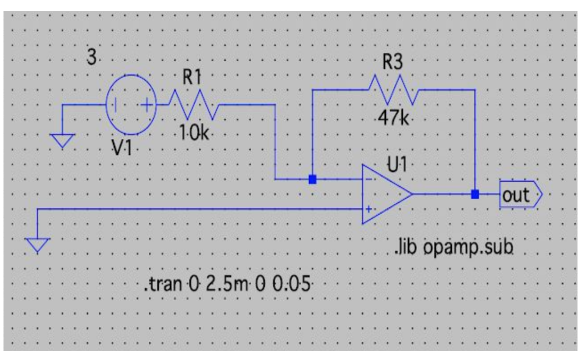
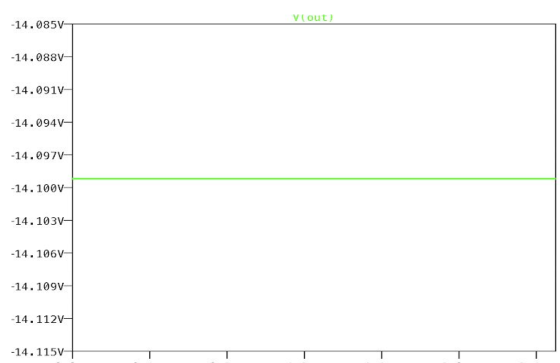
<tr><td>
</td><td>
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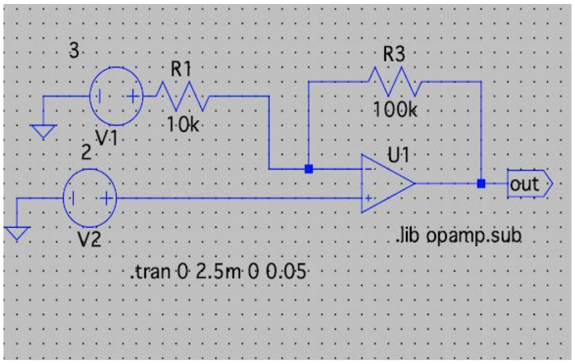
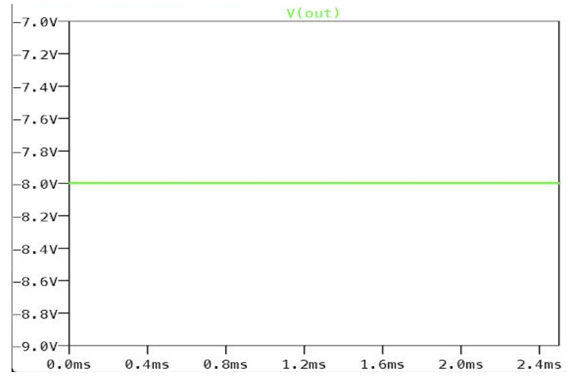
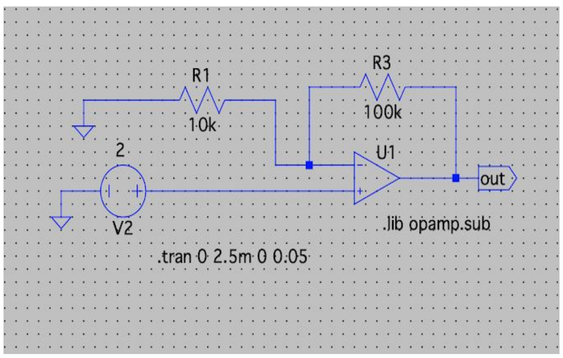
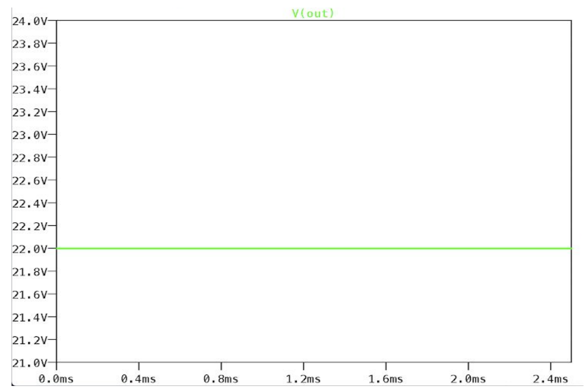
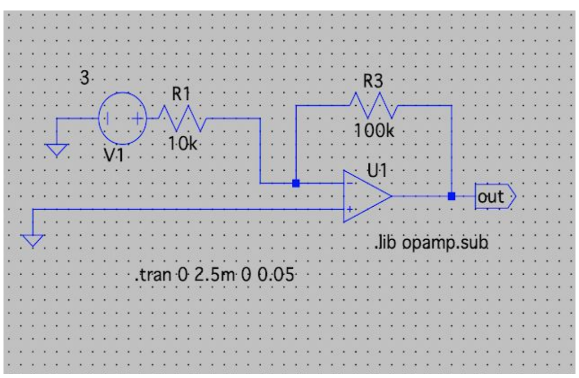
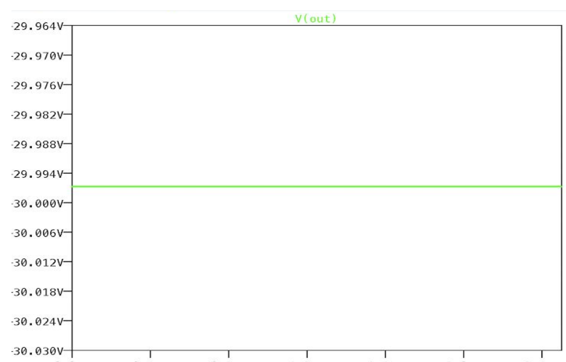
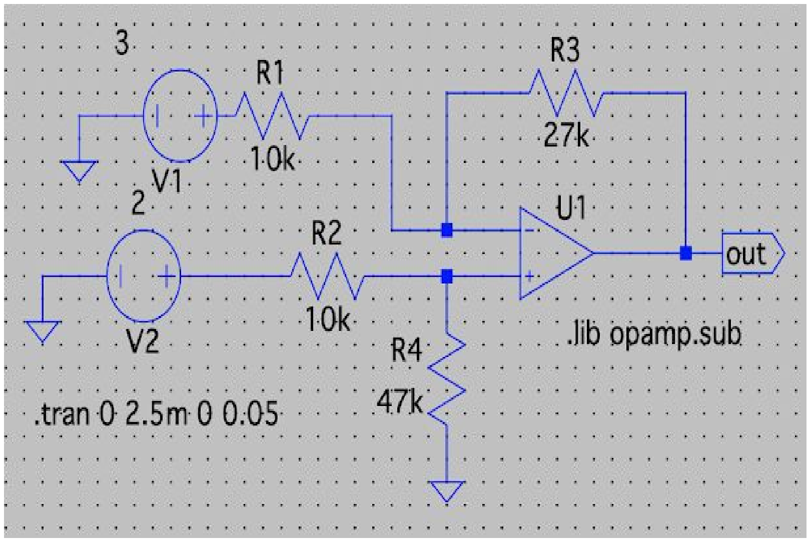
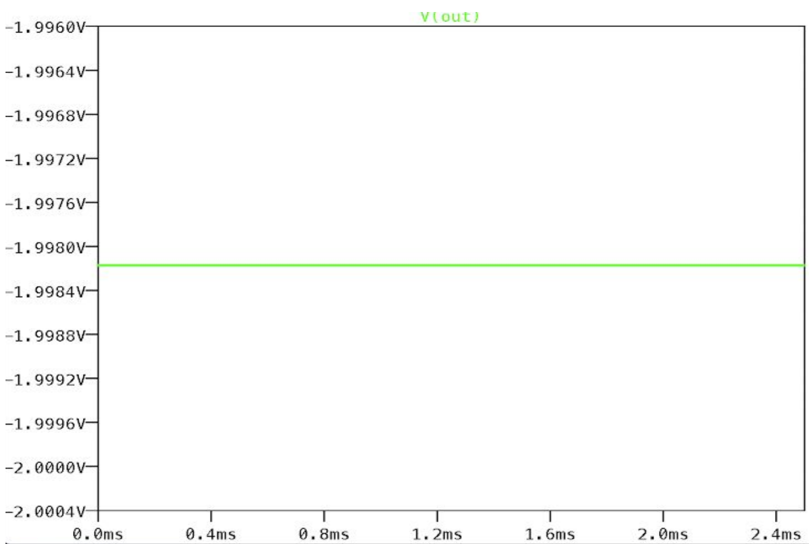
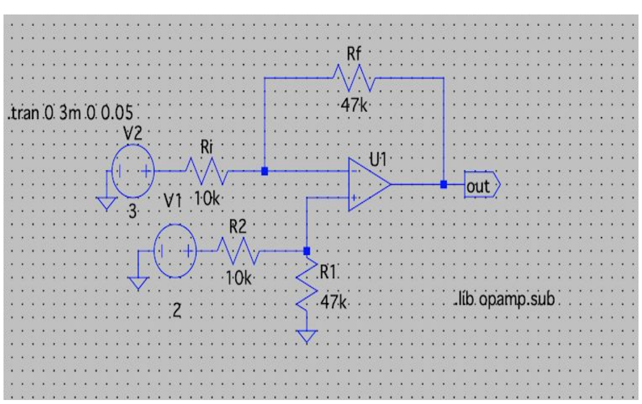
Rf = 100kΩ	Graphs
	
	
	

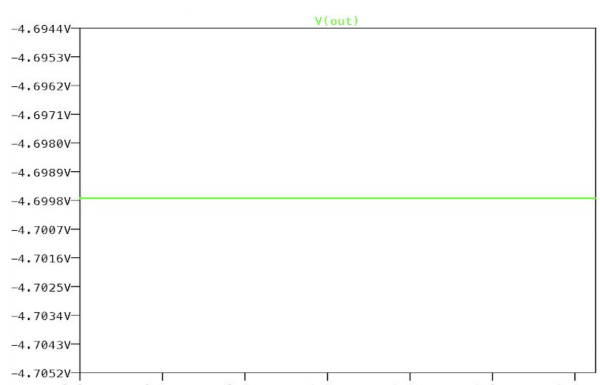
6) b) <u>Differential Amplifier</u>



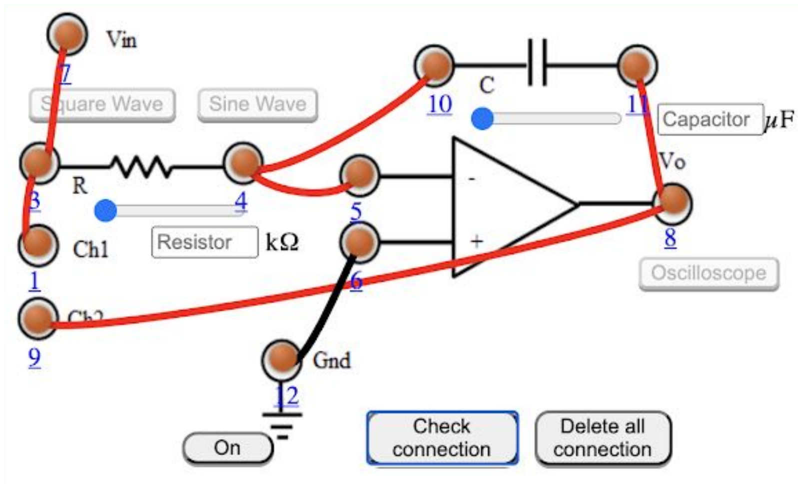


For Rf = 47kΩ



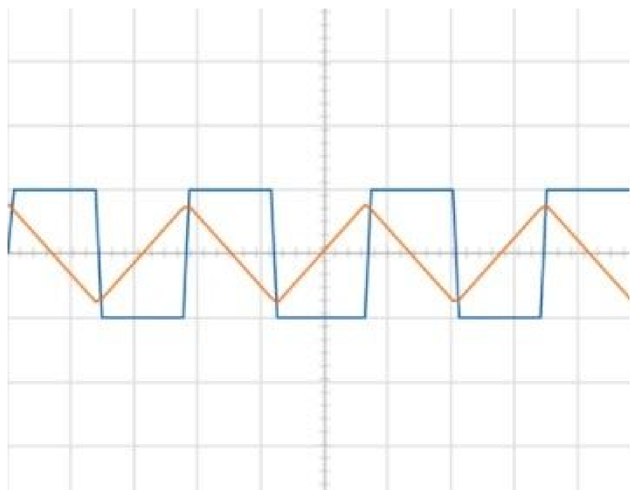


7) Integrator (Resistance(R) = 10kΩ , Capacitance(C) = 0.1µ)

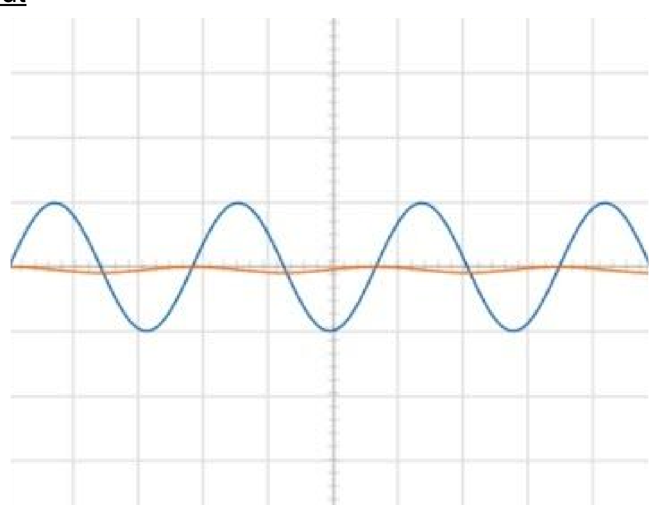


Circuit for Op-Amp Integrator

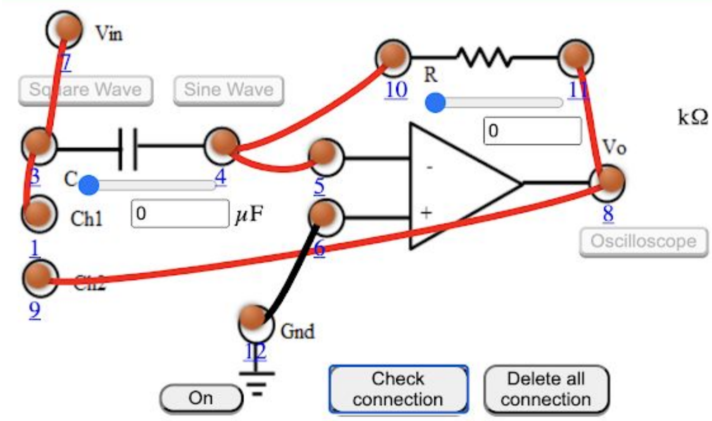
a) Square Wave Input



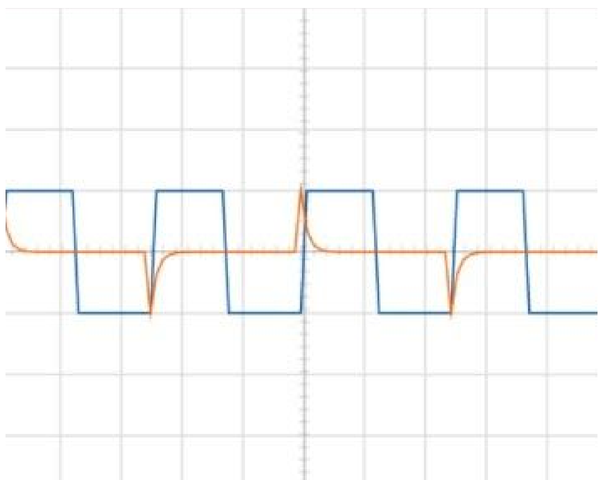
b) Sine Wave Input



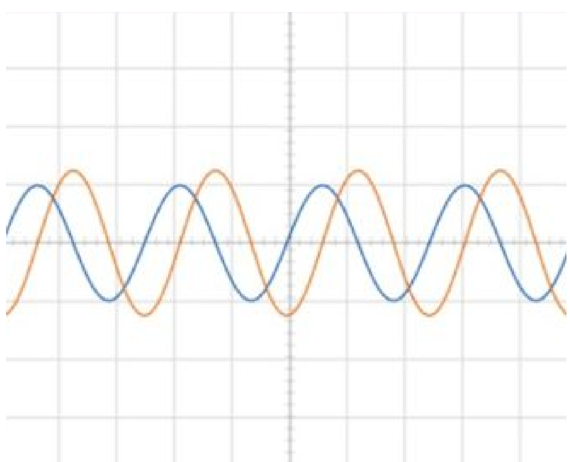
8) Differentiator (Resistance(R) = 10kΩ , Capacitance(C) = 0.1μ)



a) Square Wave Input



b) Sine Wave Input



Calculations

Finding gain and Vout for Inverting Op-Amp

a) $R_i = 10\,k\Omega$

$R_{out} = 10\,k\Omega$

$$V_{out} = -\left(\frac{R_f}{R_i}\right) \times V_{in}$$

$$\therefore V_{out} = -\frac{10}{10} \times 1 = -1V$$

$$\text{Gain} = \frac{V_{out}}{V_{in}} = -1$$

b) $R_i = 10\,k\Omega$

$R_f = 27\,k\Omega$

$$V_{out} = -\left(\frac{R_f}{R_i}\right) \times V_{in}$$

$$\therefore V_{out} = \frac{27}{10} \times 1 = -2.7\,V$$

$$\text{Gain} = \frac{V_{out}}{V_{in}} = -2.7$$

c) $R_i = 10\,k\Omega$

$R_f = 47\,k\Omega$

$$V_{out} = -\left(\frac{R_f}{R_i}\right) \times V_{in}$$

$$= -\frac{47}{10} \times 1 = -4.7V$$

$$\text{Gain} = \frac{V_{out}}{V_{in}} = -4.7$$

d) $R_i = 10\,k\Omega$

$R_f = 100\,k\Omega$

$$V_{out} = -\left(\frac{R_f}{R_i}\right) \times V_{in}$$

$$= -\frac{100}{10} \times 1 = -10V$$

$$\text{Gain} = \frac{V_{out}}{V_{in}} = -10$$

In most cases, $V_{out} \approx V_{theoretical}$

For virtual ground,

$R_f = 100\,k\Omega$

$V_{pin_1} = 0V \qquad V_{pin_2} = 1.34 \times 10^{-5}\,V$

$$\Rightarrow V_{pin_1} = V_{pin_2}$$

For Voltage Follower,

$V_{out} = 0.99\,V \approx 1V = V_{in}$

Maximum and Minimum Voltages are :

$V_{min} = -11\,V$

$V_{max} = 11V$

For Adder,

$V_{out} = -4.9998V$

$V_{out}|_{theoretical} = -5V$

$V_{out} \approx V_{out}|_{theoretical}$

For summing Amplifier,

$V_{out} = -6V$

$V_{out}|_{Theoretical} = V_p + V_{offset}$

$= 1 - 7V$

$= -6V$

$\therefore\ V_{out} = V_{out}|_{Theoretical}$

For Non-Inverting Frequency Response,

S.No.	Rf (kΩ)	Gain (Av)	Bandwidth (kHz)	Gain × Bandwidth (kHz)
1	27	3.68	306.28	1127.07
2	47	5.67	178.41	1011.58
3	100	10.998	84.08	924.71

For Rf = 27 kΩ, Av = 3.68

$\beta = Ri/(Ri + Rf)$ = 10/37 = 0.27

$Av = Ao$ 1 + βAo

=> Ao = 575

For Superposition,

$R_f = 10k\Omega, R_1 = 10k\Omega$

$V_{out} = 1V$ $\quad V_{out_1} = 3.999V$ $\quad V_{out_2} = -2.999V$

$\therefore V_{out_1} + V_{out_2} = 1V$

$V_{out} = V_{out_1} + V_{out_2}$

$R_f = 47k\Omega, R_1 = 10k\Omega$

$V_{out} = -2.7V$ $\quad V_{out_1} = 11.4V$ $\quad V_{out_2} = -14.9V \approx -14.1V$

$V_{out_1} + V_{out_2} \approx -2.7V$

$\therefore V_{out} = V_{out_1} + V_{out_2}$

$R_f = 100k\Omega, \quad R_1 = 10k\Omega$

$V_{out} = -8V$ $\quad V_{out_1} = 22.0V$ $\quad V_{out_2} \approx -30.00V$

$V_{out_1} + V_{out_2} = -8V$

$\therefore V_{out} = V_{out_1} + V_{out_2}$

For Differential Amplifier,

$R_f = 27k\Omega, \quad R_1 = 10k\Omega$

$V_{out} = -1.9982V$

$$V_{cal} = V_2 \left(\frac{R_2}{R_2 + R_3}\right)\left(1 + \frac{R_f}{R_1}\right) - V_1\left(\frac{R_f}{R_1}\right)$$

$= -1.998V$

$\therefore V_{out} \approx V_{cal}$

Similarly for $R_f = 47k\Omega$, we observe $V_{out} \approx V_{cal}$.

Discussion:

- The basic Op-amp construction is of a 3-terminal device, with 2- inputs and 1-output.
- An Operational Amplifier operates from either a dual positive (+V) and a corresponding negative (-V) supply, or they can operate from a single DC supply voltage.
- The two main laws associated with the operational amplifier are that it has an infinite input impedance, ($Z = \infty$) resulting in "No current flowing into either of its two inputs" and zero input offset voltage V1 = V2.
- Op-amps can be connected into two basic configurations, Inverting and Non-inverting. By adding more input resistors to either the inverting or non-inverting inputs Voltage Adders or Summers can be made.
- Voltage follower op-amps can be added to the inputs of Differential amplifiers to produce high impedance Instrumentation amplifiers.
- The Differential Amplifier produces an output that is proportional to the difference between the two input voltages.
- The Integrator Amplifier produces an output that is the mathematical operation of integration. The Differentiator Amplifier produces an output that is the mathematical operation of differentiation.
- Both the Integrator and Differentiator Amplifiers have a resistor and capacitor connected across the opamp and are affected by its RC time constant.

Conclusion:

- The Non-inverting Amplifier does not invert the input signal or produce an inverting signal but instead amplifies it by the ratio of $RA+(RB/RB)$ or commonly $1 + (RA/RB)$.
- The input signal is connected to the non-inverting (+) input. The Inverting Amplifier both inverts and amplifies the input signal by the ratio of $- RA/RB$.
- The gain of the amplifier is controlled by negative feedback using the feedback resistor RA and the input signal is fed to the inverting (–) input.
- The Voltage Follower, also called a buffer does not amplify or invert the input signal but instead provides isolation between two circuits. The input impedance is very high while the output impedance is low avoiding any loading effects within the circuit. As the output is connected back directly to one of the inputs, the overall gain of the buffer is +1 and Vout = Vin.
- The Adder, also called a summing amplifier, produces an inverted output voltage which is proportional to the sum of the input voltages V1 and V2. More inputs can be summed. If the input resistors are equal in value (R1 = R2 = R) then the summed output voltage is as given and the gain is +1.
- If the input resistors are unequal then the output voltage is a weighted sum and becomes: $Vo = -\ (\ (Rf/R1) \times V1 + (Rf/R2) \times V2 + etc.\ )$
- A differential amplifier uses both the inverting and non-inverting inputs to produce an output signal which is the difference between the two input voltages V1 and V2 allowing one signal to be subtracted from another. More inputs can be added to be subtracted if required.
- If resistances are equal (R = R3 and RA = R4) then the output voltage is as given and the voltage gain is +1. If the input resistance is unequal the circuit becomes a differential

amplifier producing a negative output when V1 is higher than V2 and a positive output when V1 is lower than V2.