

Introduction to Operational Amplifiers

①

Syllabus: Ideal OPAMP, Inverting and Non-inverting OP-AMP circuits, OP-AMP applications: Voltage follower, addition, subtraction, integration, differentiation, Numerical examples as applicable.

* Operational amplifier (OP-amp):

An OP-amp is a very high gain differential amplifier with high input impedance and low output impedance.

①

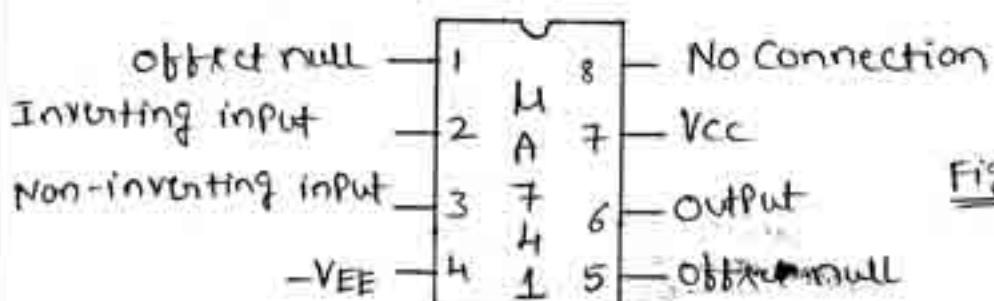
An OP-amp is a direct-coupled high-gain amplifier usually consisting of one or more differential amplifiers and usually followed by a level translator and an output stage.

Note:

- ① An OP-amp is a linear integrated circuit (IC)
- ② The OP-amp is a versatile device (Used to amplify both AC and DC input signals)
- ③ OP-amp is used to perform mathematical operations such as addition, subtraction, differentiation and integration.
- ④ Robert J. Widlar invented MA 741 IC (An internally compensated OP-amp), in 1968
MA → Fairchild (Manufacturer)
- ⑤ Advantages of OP-AMP over transistor amplifier
 - Less Power consumption
 - Low Cost
 - More compact
 - More reliable
 - Easy design
 - Versatile device
 - Higher gain can be obtained etc
- ⑥ Applications of OP-amp

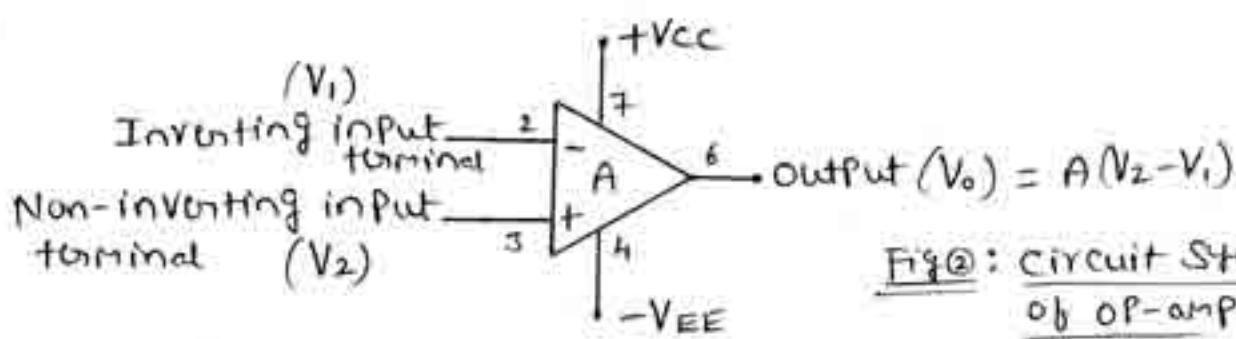
- AC and DC signal amplification
- Active filters.
- Oscillators
- Comparators
- Regulators
- Biomedical instrumentation. etc

④ Pin diagram of OP-AMP (LM 741 IC)



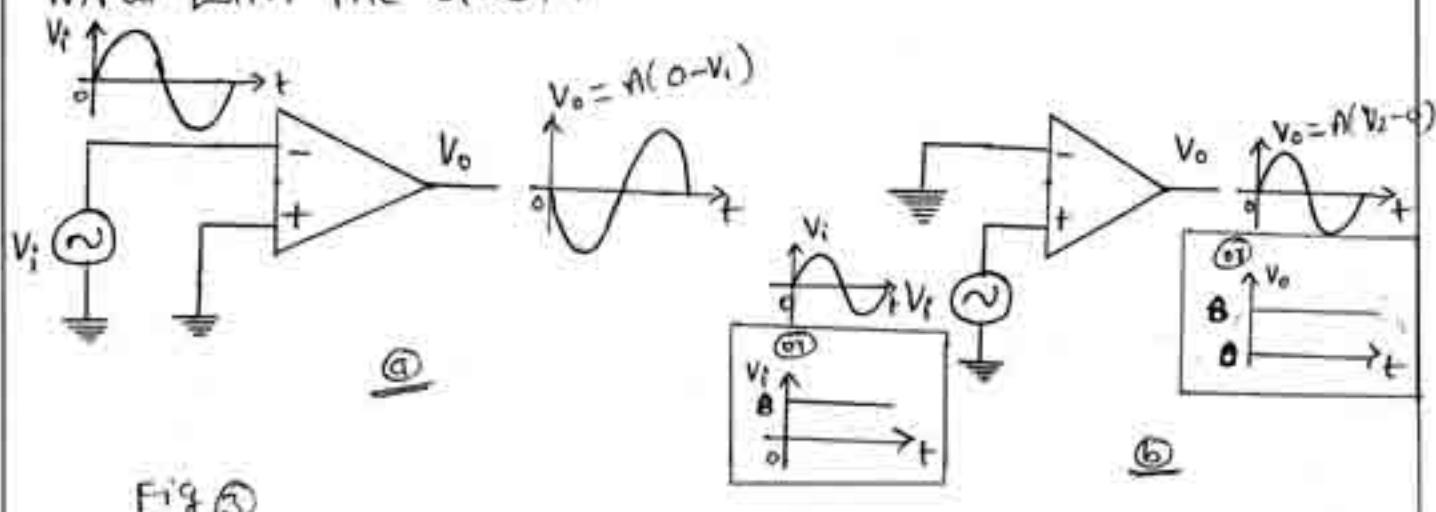
Fig①: Pin diagram of OP-AMP

⑤ Circuit Symbol of OP-AMP ⑥ Schematic Symbol



Fig②: Circuit Symbol of OP-AMP

⑦ Single-Ended Input: Input signal is connected to one input with the other input connected to ground.



Fig③

B Double-Ended (Differential) Input:

Input Signals are applied to each input

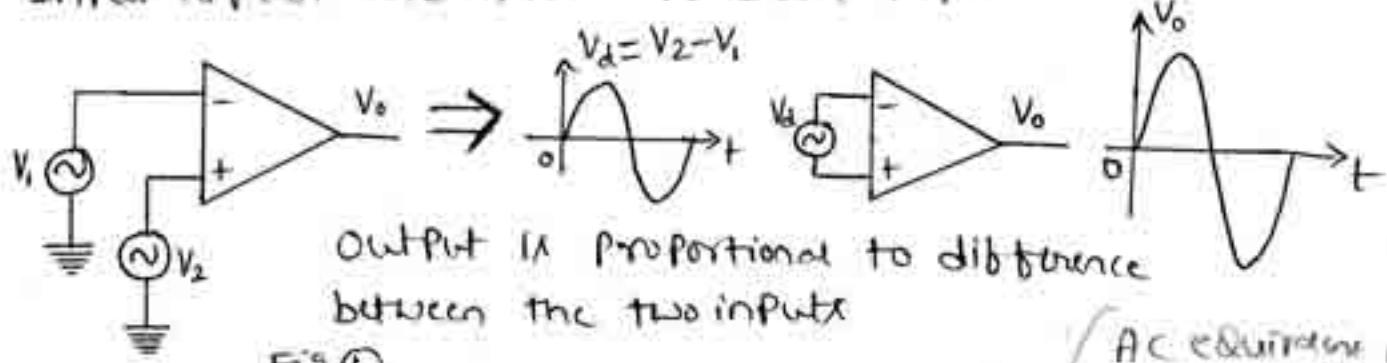


Fig ④

(AC equivalent)

⑩ Equivalent circuit of circuit model of OP-amp:

Fig ⑤ shows the simplified circuit model of Practical OP-amp.

$\rightarrow AV_d [A(V_2 - V_1)]$ is the Thevenin equivalent Voltage source, & R_o is the Thevenin equivalent resistance

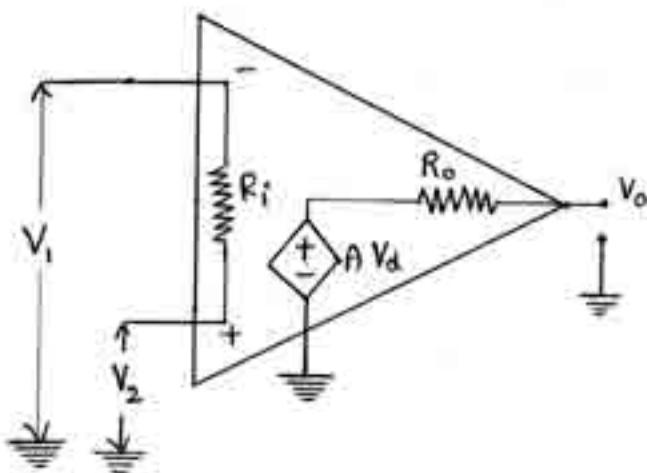


Fig ⑤: circuit model of Practical OP-amp

$\rightarrow A$ is the gain @ Large Signal Voltage Gain

$\rightarrow R_i$ is the input resistance

$\rightarrow V_d (V_2 - V_1)$ is the difference input voltage.

Fig ⑥ shows the Equivalent circuit of ideal OP-amp.

\rightarrow An ideal OP-amp has $A = \infty$, $R_i = 0$ & $R_o = 0$

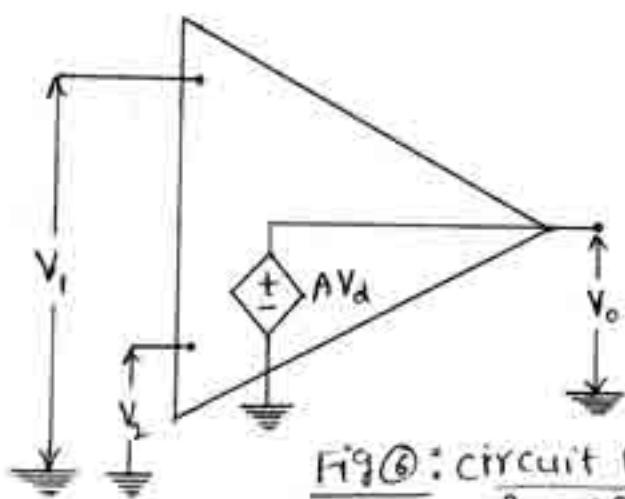


Fig ⑥: circuit Model of ideal OP-amp

(11) Package types

There are three basic types of Linear IC packages:

- The flat Pack
- The metal Can
- The dual-in-line package (DIP)

(12) Features of TFI

- No external frequency compensation required.
- Short-circuit protection.
- offset null capability
- Large common-mode and differential Voltage range.
- Low power consumption.
- No Latch-up problem.

(13) Differential amplifier :

It amplifies the difference of the two inputs $V_d(V_2 - V_1)$

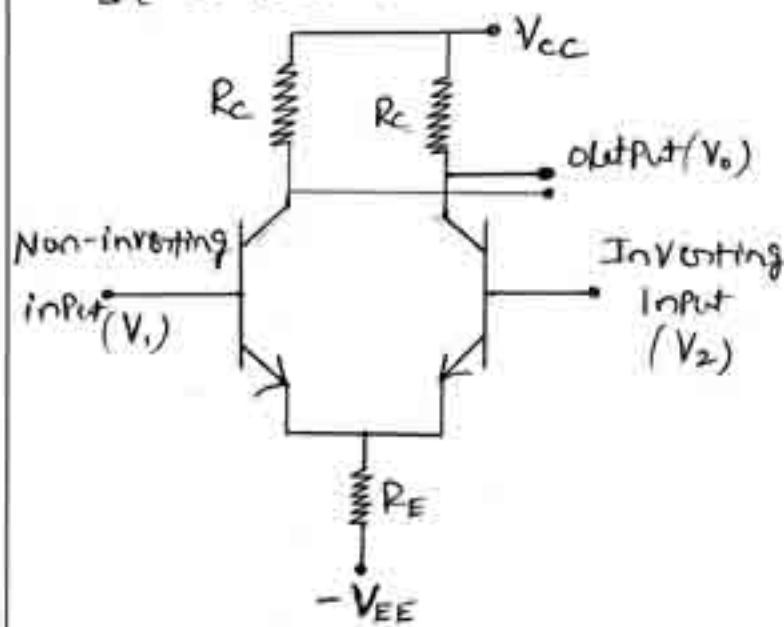


Fig (13): Differential amplifier

Output is,

$$V_o \propto (V_1 - V_2)$$

$$\Rightarrow V_o = A(V_1 - V_2) \quad (1)$$

$$V_o = AV_d$$

Where,

$A \rightarrow$ Large Signal
Voltage gain

$V_1 \rightarrow$ Voltage applied to
the non-inverting
input

$V_2 \rightarrow$ Voltage applied to
inverting input

$V_d \rightarrow$ Difference Voltage

(14) • OP-AMP which use BJT core called bipolar type opamp

• OP-AMP having FET input circuit with the remainder
of the circuit using BJT core called FET type op-amp

* Block diagram of OP-amp @ Internal Block diagram

(i) Architecture of OP-amp:

The block diagram of an OP-amp is shown in fig (8)

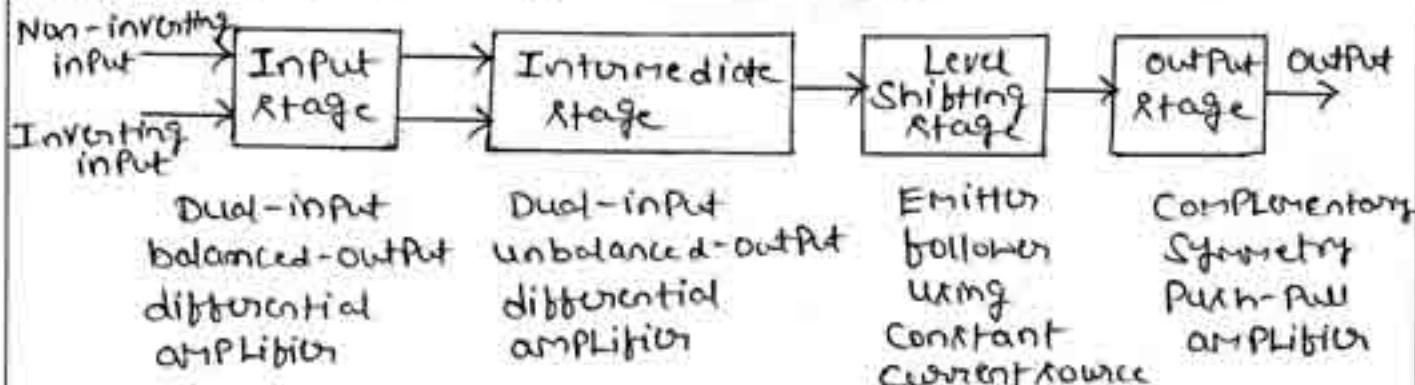


Fig (8): Block diagram of a typical OP-amp

There are four stages:

① Input Stage @ Differential amplification stage

- It can amplify difference between the two input signals.
- Input resistance is very high, draws zero current from the input source.

② Intermediate Stage (Stage 2) @ High gain amplification stage

- It uses direct coupling.
- It provides very high gain.

③ Level translator Stage @ Level Shifting Stage (Buffer)

- It shifts the dc level of the output voltage of the intermediate stage to zero.

④ Output Stage @ Power amplification stage @ Driver stage

- It has very small output resistance.
- Output voltage is the same irrespective of the value of the load resistance connected to the output terminal.

Note: (i) Configurations @ Voltage gain of OP-amp:

① Open-loop Configuration ② Open-loop Voltage gain (A_{OL})

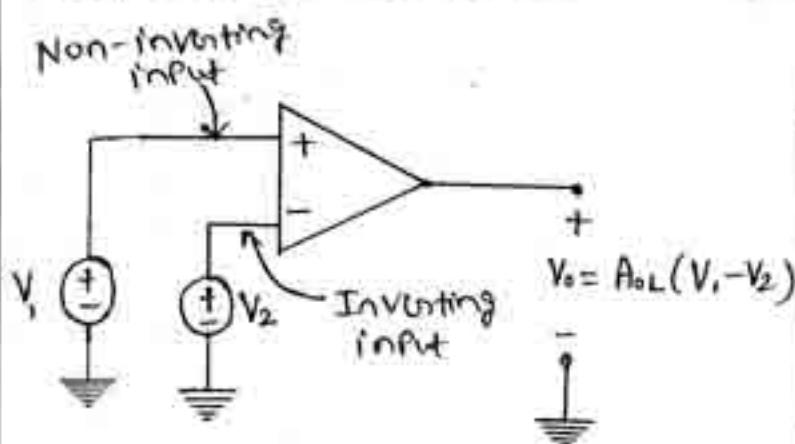


Fig ①: Open loop Configuration

- A_{OL} is the Open-loop Voltage gain of OP-AMP (Typically $A_{OL} = 2 \times 10^5$)

- A_{OL} is the Maximum Possible Voltage gain.
- There is no feedback from the output to input

- If Input is in micro Volts, Output will be in Volts.
- Output Voltage cannot cross the Value of Power Supply (Saturation Value) V_{CC} (or V_{EE})
- So, if input is in milli Volts, output reaches Saturation Value $V_{sat} = V_{CC}$ (or V_{EE}). This Property of OP-AMP is called Saturation Property.

② Closed-loop Configuration ③ Closed-loop Voltage gain (A_L)

- Open-loop Voltage gain of OP-AMP is very high. Such high gain is not required in most applications.
- In order to reduce gain, Negative feedback is used (A part of the output signal is fed back in phase opposition to the input)
- Many other OP-AMP characteristics are improved with this.

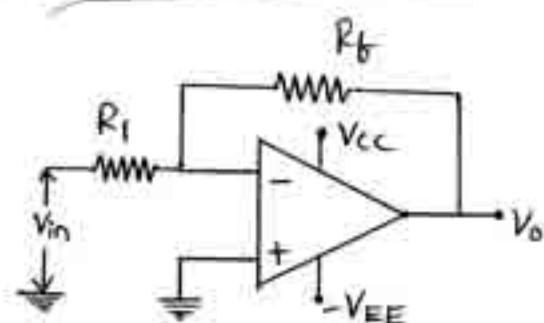


Fig ②: Negative feedback OP-AMP circuit
(Closed loop Configuration)

④ Total output of a differential amplification (practically) ⑤ (OP-AMP)

The output of OP-amp (DA) is. (7)
 $(DA \rightarrow \text{Differential Amplifier})$

$$V_o = A_d V_d - \textcircled{1}$$

Where, $A_d \rightarrow$ Differential gain (Gain with which the DA amplifies the difference between two input signals)

$V_d \rightarrow$ Difference between two inputs ($V_1 - V_2$)

If $V_1 = V_2$, then ideally output is zero. ($V_o = 0$)

But in practical OP-amp, output is.

$$V_o = A_{cm} V_{cm} - \textcircled{2}$$

$$A_{cm} = \frac{V_o}{V_{cm}}$$

Where $A_{cm} \rightarrow$ Common mode gain (Gain with which DA amplifies the common mode signal)

$V_{cm} \rightarrow$ Common mode signal ($\frac{V_1 + V_2}{2}$)

∴ Total output is,

$$V_o = A_d V_d + A_{cm} V_{cm}$$

$$V_o = A_d V_d \left(1 + \frac{1}{CMRR} \frac{V_{cm}}{V_d} \right) \quad \boxed{\therefore CMRR = \frac{A_d}{A_{cm}}}$$

III $A_d (\text{dB}) = 20 \log_{10} (A_d)$

E OP-AMP parameters @ Characteristics

Large Signal Voltage Gain (A)

① Differential gain @ Differential Mode Gain (A_d)

It is the factor by which the difference between the two input signals is amplified by the OP-amp.

②

It is the ratio of the output voltage to the difference voltage. It is denoted by A_d

$$\text{i.e. } A_d = \frac{V_o}{V_d} = \frac{V_o}{V_1 - V_2}$$

Ideally: $A_d = \infty$

Practically: $A_d = A = 2 \times 10^5$
(HA741)

② Common mode gain (A_{CM})

It is the factor by which the common mode input voltage is amplified by the OP-amp.

It is the ratio of the output voltage to the common mode signal. It is denoted by ' A_{CM} '.

$$\text{i.e. } A_{CM} = \frac{V_o}{V_{CM}} = \frac{V_o}{(V_1 + V_2)/2}$$

Ideally: $A_{CM} = 0$

Practically: $A_{CM} = 6 - 7$
(HA741)

③ Common mode rejection ratio (CMRR)

It is the factor which explains the ability of an OP-amp to reject the common mode signal.

It is the ratio of differential gain to common mode gain. It is denoted by 'CMRR'.

$$\text{i.e. } CMRR = \frac{A_d}{A_{CM}} \quad @ \quad CMRR(\text{dB}) = 20 \log_{10} \left(\frac{A_d}{A_{CM}} \right) \text{ (dB)}$$

Ideally: $CMRR = \infty$

Practically: $CMRR = 90 \text{ dB}$
(HA741)

A_d is known as large-signal
voltage gain (A)

④ Differential input resistance @ Input resistance @

Input impedance (R_i)

It is the equivalent resistance measured at either the inverting @ non-inverting input terminal with the other terminal connected to ground. It is denoted by ' R_i '.

Ideally: $R_i = \infty$

Practically: $R_i = 2 \text{ M}\Omega$ (For HA741)

⑤ Output resistance @ Output impedance (R_o)

⑦

It is the equivalent resistance measured between the output terminal of the OP-amp and the ground. It is denoted by R_o .

Ideally: $R_o = 0$

Practically: $R_o = 75\Omega$ (MATHIC)

⑥ Bandwidth (BW)

It is the range of frequency over which the gain of OP-amp is almost constant.

It is the range of frequency over which the performance of the OP-amp is satisfactory. It is denoted by BW.

MATHIC is
done at 741C

Ideally: $BW = \infty$

Practically: $BW = 1\text{MHz}$ (741C)

⑦ Input Offset Voltage (V_{io})

It is the voltage that must be applied between the two input terminals of an OP-amp to make output voltage zero (to null the output). It is denoted by V_{io} .

Ideally: $V_{io} = 0$

Practically: $V_{io} = 6\text{mV}$ (741C)

$$V_{io} = V_1 - V_2 \text{ for } V_o = 0$$

$$V_o = 0$$

⑧ Output Offset Voltage (V_{oo})

It is the output voltage when both input voltages are zero. It is denoted by V_{oo} .

Ideally: $V_{oo} = 0$

Practically: $V_{oo} = 1\text{mV}$ (741C)

⑨ Input Offset Current (I_{io})

It is the difference between the currents in the input terminals. It is denoted by I_{io} .

$$\text{i.e. } I_{io} = |I_1 - I_2|$$

Where, $I_1 \rightarrow$ current into the noninverting input

$I_2 \rightarrow$ current into the inverting input.

Ideally: $I_{io} = 0$

Practically: $I_{io} = 20\text{nA}$ (For MA 741)

20nA nom

⑩ Input bias current (I_{ib})

It is the average of the currents in the input terminals. It is denoted by I_{ib} .

$$\text{i.e. } I_{ib} = \frac{I_1 + I_2}{2}$$

Where, $I_1, I_2 \rightarrow$ current into non-inverting & inverting input respectively.

Ideally: $I_{ib} = 0$

Practically: $I_{ib} = 80\text{nA}$ (For MA 741)

80nA typ

⑪ Slew rate (SR)

It is the maximum rate of change of output voltage with respect to time. It is denoted by SR.

$$\text{i.e. } SR = \left. \frac{dV_o}{dt} \right|_{\max} (\text{V/}\mu\text{s})$$

Ideally: $SR = \infty$

Practically: $SR = 0.5\text{V/}\mu\text{s}$

⑫ Supply voltage rejection ratio @ power supply sensitivity @ Power supply rejection ratio: (SVRR) @ (PSRR)

It is the change in input offset voltage (V_{io}), caused by variations in supply voltage. It is denoted

by SVRR & PSRR.

$$\text{ie } \text{SVRR} = \frac{\Delta V_{o}}{\Delta V} (\mu\text{V/V})$$

Ideally: $\text{SVRR} = 0$

Practically: $\text{SVRR} = 150 \mu\text{V/V}$ (741C)

Note:

① Input Capacitance (C_i):

It is the equivalent capacitance measured at either the inverting or noninverting terminal with the other terminal connected to ground. It is defined by ' C_i '.

Practically: $C_i = 1.4 \text{ pF}$ for 741C

② Gain-Bandwidth product (G_B)

It is the bandwidth of the OP-amp when the voltage gain is 1

Practically: $G_B = 1 \text{ MHz}$ for 741C

③ Maximum signal frequency in terms of Slew rate
(for an undistorted output)

Let the output voltage (sinusoidal signal) be.

$$V_o = V_m \sin(\omega t) \quad \text{--- (1)}$$

Diffr w.r.t 't' on b.x

$$\frac{dV_o}{dt} = V_m \cos(\omega t) \cdot \omega$$

$$\Rightarrow \left. \frac{dV_o}{dt} \right|_{\max} = \omega V_m \quad \text{--- (2)} \quad (\because \cos(\omega t)|_{\max} = 1)$$

To prevent distortion at the output, the rate of change of output w.r.t time must be less than the SR.

i.e. $\left. \frac{dV_o}{dt} \right|_{\text{max}} \leq SR - ③$

Using ② in ③, we get,

$$\omega V_m \leq SR$$

$$\Rightarrow \omega \leq \frac{SR}{V_m} \Rightarrow \omega_{\text{max}} = \frac{SR}{V_m} \text{ (rad/s)}$$

$$\Rightarrow f \leq \frac{SR}{2\pi V_m} \quad (\because \omega = 2\pi f) \quad f_{\text{max}} = \frac{SR}{2\pi V_m} \text{ (Hz)}$$

④ OP-amp characteristics:

SL No.	Parameter	Symbol	Ideal Value	Typical Value for LM741
1	Differential gain @ Large Signal Voltage gain @ Open-loop Voltage gain.	$A_d @ A$	∞	2×10^5
2	Common mode gain	A_{cm}	0	6
3	Common mode rejection ratio	CMRR	∞	90dB
4	Input resistance	R_i	∞	$2M\Omega$
5	Output resistance	R_o	0	75Ω
6	Bandwidth	BW	∞	1MHz
7	Input offset voltage	V_{io}	0	6mV
8	Output offset voltage	V_{oo}	0	1mV
9	Input offset current	I_{io}	0	20nA
10	Input bias current	I_{ib}	0	80nA
11	Supply voltage rate	SR	∞	0.5V/mV
12	Supply voltage rejection ratio	SVRR	0	150mV/V

⑤ Virtual ground @ Virtual short :

The OP-amp inverting amplifier is shown in fig ⑪

The output voltage is,

$$V_o = A(V_2 - V_1) \quad \text{--- (1)}$$

Where, $A \rightarrow$ Large Signal Voltage gain

For an output voltage of 12V, the input voltage would be.

$$V_2 - V_1 = \frac{V_o}{A} \quad (\because \text{From 1})$$

$$\Rightarrow V_2 - V_1 = \frac{12}{2 \times 10^5} \quad (\because \text{Practically, } A = 2 \times 10^5 \text{ for MA 741})$$

$$\Rightarrow V_2 - V_1 = 0.06 \text{ mV}$$

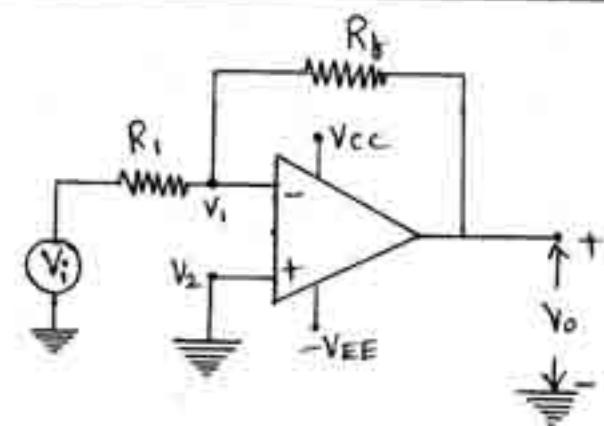
Differential input voltage is very small. ($V_d = V_2 - V_1$)

Ideally, $V_2 - V_1 = 0$

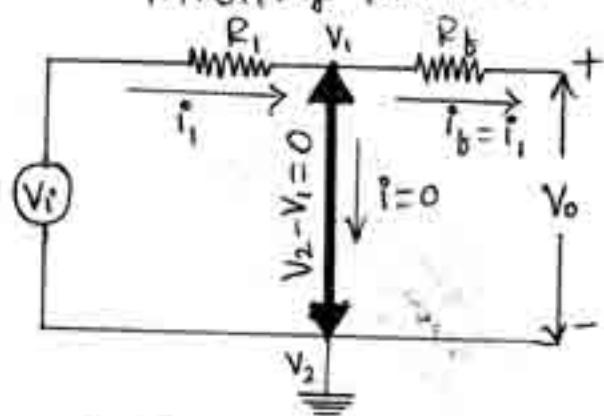
$$\Rightarrow V_1 = V_2 \quad \text{--- (2)}$$

From (2), we can conclude,

- Voltage at inverting terminal = Voltage at non-inverting terminal
- There exists a virtual short circuit @ virtual ground
- No current flows through the short circuit
- Current through R_i = Current through R_f .



Fig(11): Basic OP-amp circuit



Fig(12): Virtual ground

(6) The virtual short is indicated by a thick line between input terminals.

(7) For an op-amp, output voltage cannot cross V_{cc} (V_{EE}) (≈ 12 to $15V$) (\because from Saturation Property)

(4) ⑥ No current flows into OP-amp input terminals (∴ Input impedance is very high)

* OP-amp applications

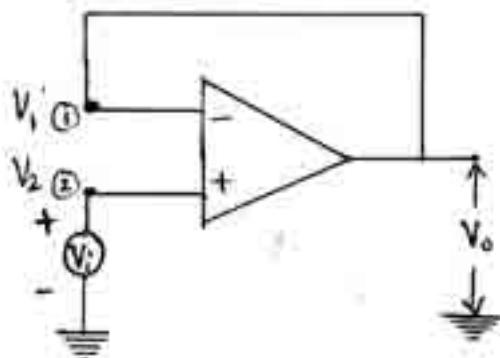
- ① Voltage follower
- ② Inverting amplifier
- ③ Non-inverting amplifier
- ④ Summer (Adder)
- ⑤ Subtractor (difference amplifier)
- ⑥ Differentiator
- ⑦ Integrator

⑧ Isolation amplifier ⑨ Source follower

* ⑩ Voltage follower ⑪ Unity gain amplifier ⑫ Buffer:

Definition: An OP-amp circuit in which the output voltage follows the input voltage is called Voltage follower (Output voltage is equal to input voltage)

Circuit diagram:



Analytic:

From virtual ground concept,

$$V_1 = V_2 = V_i \quad \text{--- (1)}$$

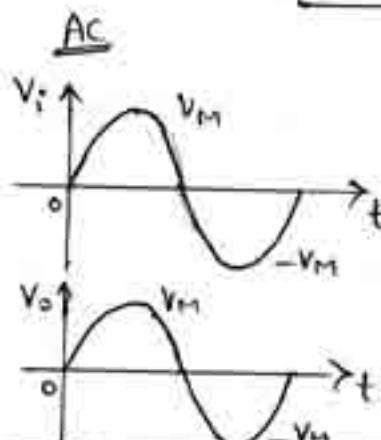
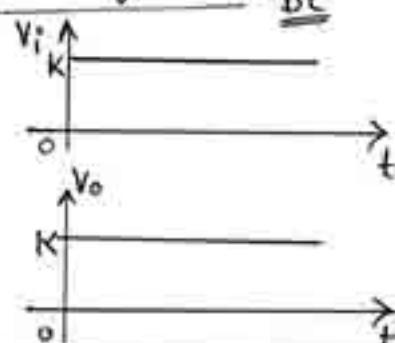
Since output is connected to input,

$$V_0 = V_i \quad \text{--- (2)}$$

From (1) & (2),

$$\boxed{V_0 = V_i} \quad \text{--- (3)}$$

Waveforms: DC



Conclusion:

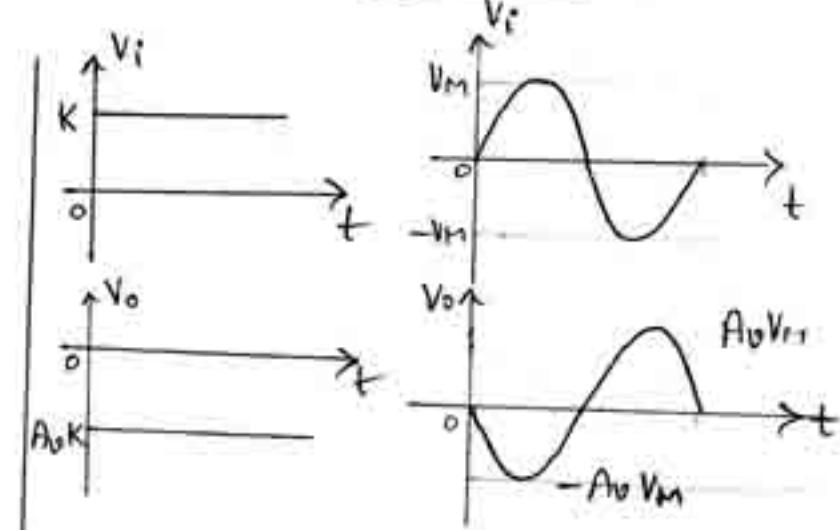
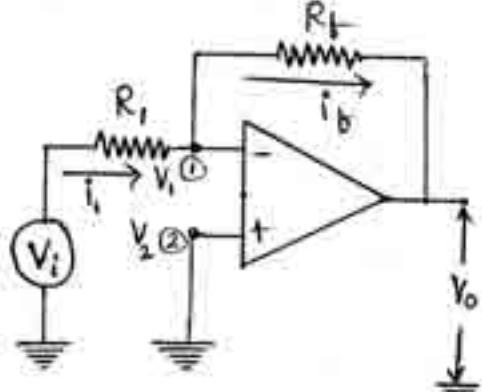
- From eqn(3), the output voltage follows the input voltage

*② Inverting amplifier:

Definition: An OP-AMP circuit in which the output voltage is out of phase (180°) with respect to the input voltage is called inverting amplifier.

Waveforms:

Circuit diagram:



Analysis:

Applying KCL at node ①.

$i_1 = i_b$ (Since input impedance of OP-AMP is very high, no current flows into OP-AMP input terminals)

$$\Rightarrow \frac{V_i - V_1}{R_1} = \frac{V_1 - V_o}{R_f}$$

$$\Rightarrow \frac{V_i}{R_1} = -\frac{V_o}{R_f} \quad \left[\text{From virtual ground concept.} \right]$$

$$\Rightarrow \boxed{V_o = -\left(\frac{R_f}{R_1}\right)V_i} \quad @ \quad \boxed{\frac{V_o}{V_i} = -\frac{R_f}{R_1} = A_v} \quad -⑤$$

Where,

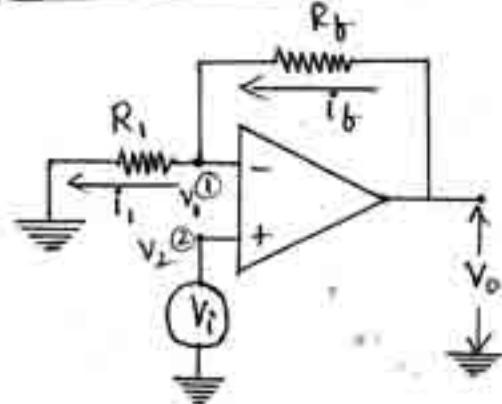
$A_v \rightarrow$ Closed loop Voltage gain

Conclusion: From eqn(5), negative sign indicates that the output is inverted w.r.t the input.

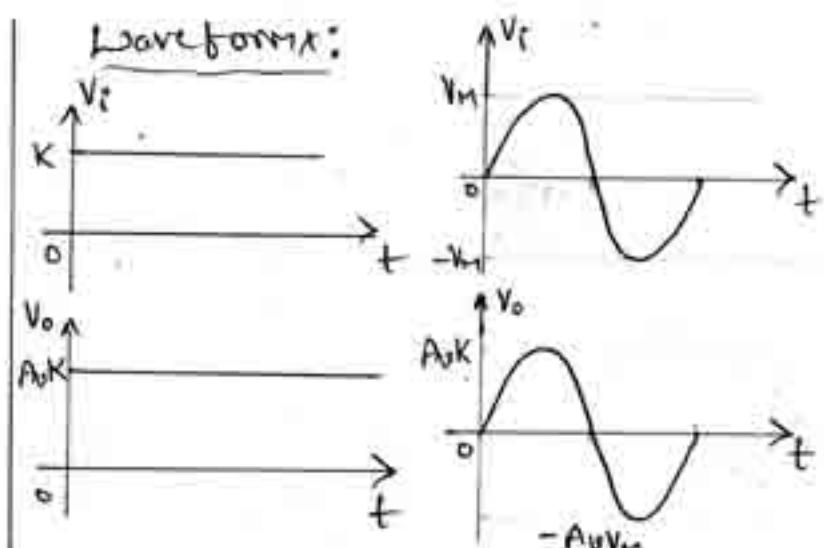
③ Non-inverting amplifier:

Definition: An op-amp circuit in which the output voltage is in phase with the input voltage is called Non-inverting amplifier.

Circuit diagram:



Waveforms:



Analysis:

APPLYING KCL at node ①.

$$i_b = i_1 \quad (\because \text{No current flows into op-amp input terminals})$$

$$\Rightarrow \frac{V_o - V_i}{R_f} = \frac{V_i - 0}{R_1} \quad (\text{From virtual ground concept.}) \quad V_1 = V_2 = V_i$$

$$\Rightarrow \frac{V_o - V_i}{R_f} = \frac{V_i}{R_1}$$

$$\Rightarrow \frac{V_o - V_i}{V_i} = \frac{R_f}{R_1}$$

$$\Rightarrow \frac{V_o}{V_i} - 1 = \frac{R_f}{R_1}$$

$$\Rightarrow \boxed{\frac{V_o}{V_i} = 1 + \frac{R_f}{R_1} = A_v} \quad \textcircled{6} \quad \boxed{V_o = \left(1 + \frac{R_f}{R_1}\right) V_i} \quad \textcircled{7}$$

Where, $A_v \rightarrow$ closed loop Voltage gain.

Conclusion: From ⑥ @ ⑦, • The output voltage is in-phase with the input voltage. • A_v depends on $R_f & R_1$.

* (i) Summer (addit.) @ Summing amplifier:

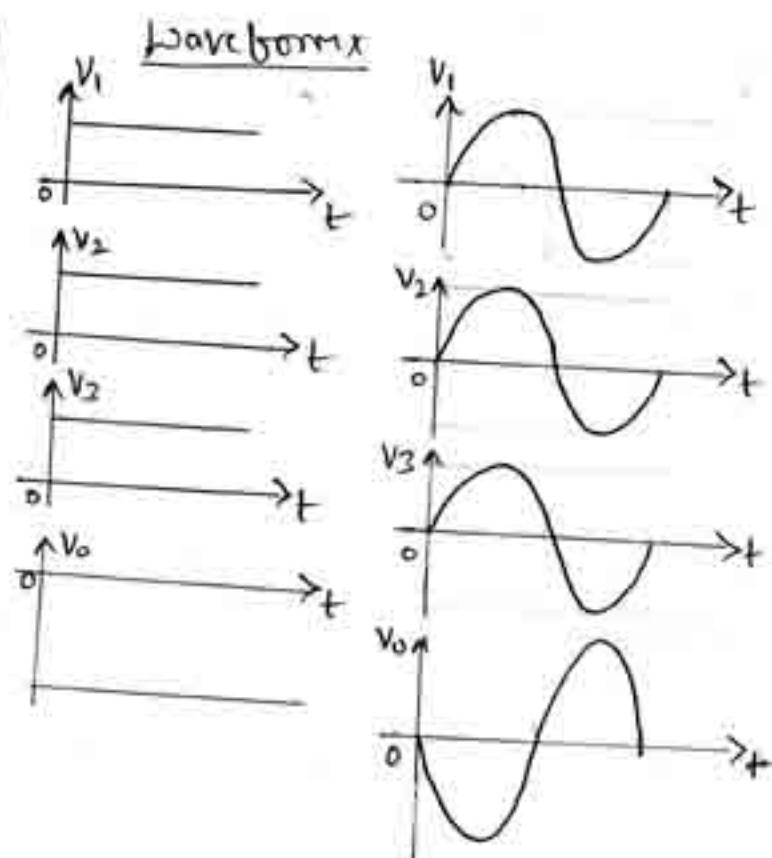
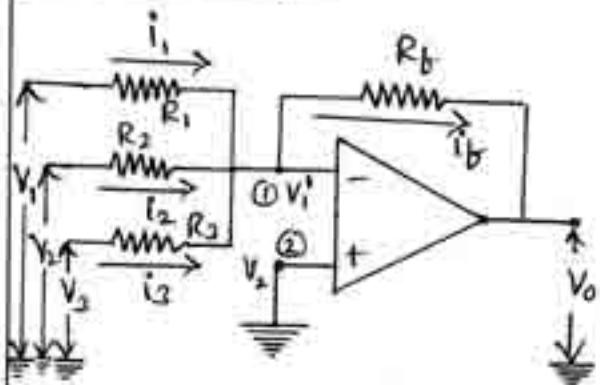
Definition: An op-amp circuit, in which the output voltage is the sum of the input signal voltages is called Summer.

There are ~~two~~ ^{two} types:

(a) Inverting summing amplifier:

Definition: An op-amp circuit, in which the output voltage is the inverted sum of the input voltage is called inverting summing amplifier.

Circuit diagram



Analysis:

APPLYING KCL at node ①.

$$i_1 + i_2 + i_3 = i_b \quad (\because \text{No current flows into op-amp input terminals})$$

$$\Rightarrow \frac{V_1 - V_i'}{R_1} + \frac{V_2 - V_i'}{R_2} + \frac{V_3 - V_i'}{R_3} = \frac{V_i' - V_o}{R_f}$$

$$\Rightarrow \frac{V_1}{R_1} + \frac{V_2}{R_2} + \frac{V_3}{R_3} = -\frac{V_o}{R_f} \quad (\text{From virtual ground concept, } V_i' = V_2 = 0)$$

$$\Rightarrow V_o = - \left(\frac{R_f}{R_1} V_1 + \frac{R_f}{R_2} V_2 + \frac{R_f}{R_3} V_3 \right) \quad \text{--- (8)}$$

Conclusion:

From (8), the output voltage is proportional to the inverted sum of the input voltages.

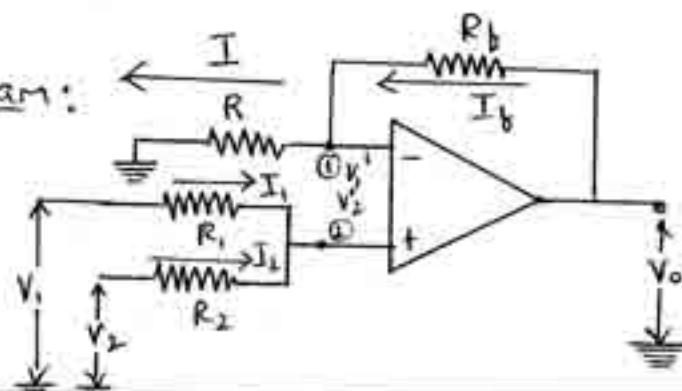
Note:

- ① From (4), if $R_f = R_1$, $V_o = -V_i$ $\frac{V_o}{V_i} = -1 = A_v$
amplification is unity gain inverting amplifier.
- ② From (7), • Irrespective of the value of R_1 & R_f , $V_o \geq V_i$
• If $R_f = 0$ or $R_1 = \infty$, then $V_o = V_i$, amplification is unity gain non-inverting amplifier.
- ③ From (8), • If $R_1 = R_2 = R_3 = R_f$, then, $V_o = -(V_1 + V_2 + V_3)$
output voltage is the negative of the sum of the input voltages [gain of the summer is unity (1)]
- If $R_1 = R_2 = R_3 = 3R_f$, then, $V_o = -\frac{(V_1 + V_2 + V_3)}{3}$
- If $R_1 = R_2 = 2R_f$ & $V_3 = 0$, then $V_o = -\frac{(V_1 + V_2)}{2}$
then circuit is averager or averaging circuit

Non-inverting Summer:

Definition: An op-amp circuit, in which the output voltage is the sum of the input voltages is called Non-inverting Summer.

Circuit diagram:



Analytic:

APPLYING KCL at node ②

$$I_1 + I_2 = 0 \quad (\text{NO current flows into input})$$

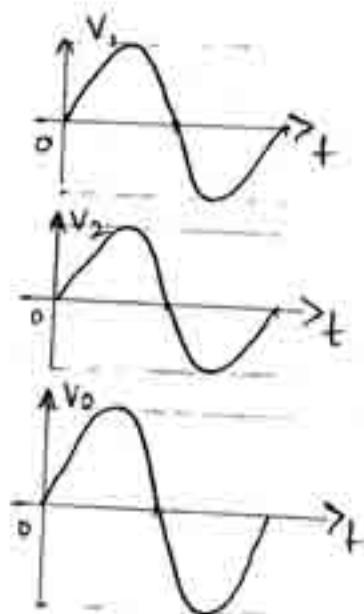
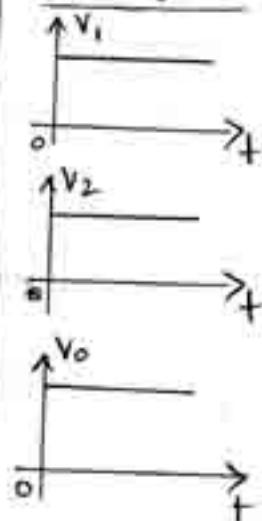
$$\Rightarrow \frac{V_1 - V_2'}{R_1} + \frac{V_2 - V_2'}{R_2} = 0$$

$$\Rightarrow \frac{V_1}{R_1} + \frac{V_2}{R_2} = V_2' \left(\frac{1}{R_1} + \frac{1}{R_2} \right)$$

$$\Rightarrow \frac{R_2 V_1 + R_1 V_2}{R_1 R_2} = V_2' \left(\frac{R_2 + R_1}{R_1 R_2} \right)$$

$$\Rightarrow V_2' = \frac{R_2 V_1 + R_1 V_2}{R_1 + R_2} \quad \text{---} ①$$

Waveforms



APPLYING KCL at node ①.

$$I_b = I$$

$$\Rightarrow \frac{V_o - V_1'}{R_b} = \frac{V_1' - 0}{R}$$

$$\Rightarrow \frac{V_o}{R_b} = V_1' \left(\frac{1}{R} + \frac{1}{R_b} \right)$$

$$\Rightarrow \frac{V_o}{R} = V_1' \left(\frac{R_b + R}{R_b R} \right)$$

$$V_o = V_1' \left(\frac{R + R_b}{R} \right) \quad \text{---} ⑩ \quad \left(\begin{array}{l} \text{From Virtual Ground,} \\ V_1' = V_2' = \frac{R_2 V_1 + R_1 V_2}{R_1 + R_2} \end{array} \right)$$

$$\Rightarrow V_o = \left(\frac{R_2 V_1 + R_1 V_2}{R_1 + R_2} \right) \left(\frac{R + R_b}{R} \right)$$

$$\Rightarrow V_o = \frac{R_2(R + R_b)}{R(R_1 + R_2)} V_1 + \frac{R_1(R + R_b)}{R(R_1 + R_2)} V_2$$

$$\Rightarrow V_o = \boxed{\frac{(1 + R_b/R)}{(1 + R_1/R_2)} V_1 + \frac{(1 + R_b/R)}{(1 + R_2/R_1)} V_2} \quad \text{---} ⑪$$

Conclusion:

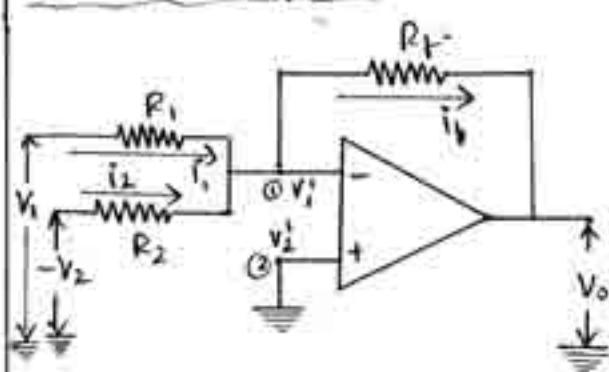
From (1), the output voltage is proportional to the sum of the input voltages.

Note: ① From (1). If $R = R_f = R_1 = R_2$, $V_o = V_1 + V_2$.
Output voltage is equal to the non-inverted sum of the input voltages. ② From (3), if $V_1, V_2 < V_3$ are negative, $V_o = \frac{R_f}{R_1} V_1 + \frac{R_f}{R_2} V_2 + \frac{R_f}{R_3} V_3$.

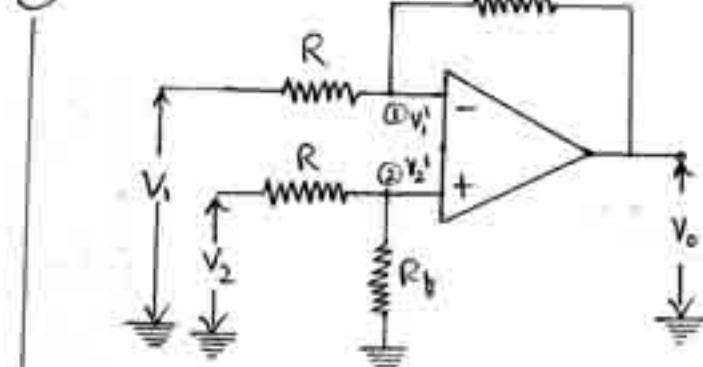
* (5) Subtractor @ Difference amplifier

Definition: An op-amp circuit, in which the output voltage is the difference (Subtraction) of two input voltages is called Subtractor.

Circuit diagram:



Q1



Applying KCL at node Q1.

$$i_1 + i_2 = i_b$$

$$\Rightarrow \frac{V_1 - V_1'}{R_1} + \frac{-V_2 - V_2'}{R_2} = \frac{V_1' - V_0}{R_f}$$

$$\Rightarrow \frac{V_1 - V_2}{R_1} = -\frac{V_0}{R_f} \quad (\because V_1' = V_2' = 0)$$

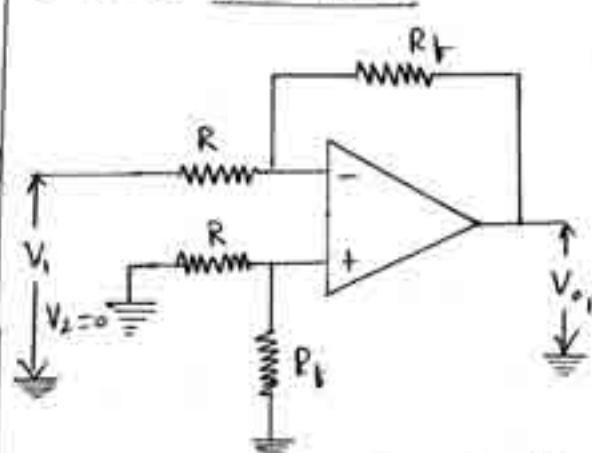
$$\Rightarrow V_o = \frac{R_f}{R_1} V_2 - \frac{R_f}{R_1} V_1 \quad \text{---(2)}$$

If $R_1 = R_2 = R_f$, then

$$V_o = V_2 - V_1 \quad \text{---(3)}$$

Let us use superposition theorem.

Case(i): Let $V_2 = 0$



The resulting circuit is inverting amplifier.

$$\therefore V_{o1} = -\frac{R_f}{R} V_1 \quad \text{---(4)}$$

Case (ii): Let $V_1 = 0$

The resulting circuit is shown in fig *

The circuit is non-inverting amplifier.

$$V_{o_2} = \left(1 + \frac{R_f}{R}\right) V_2 - (15)$$

From Potential division rule

$$V_2' = V_2 \frac{R_b}{R + R_b} - (16)$$

Using (16) in (15). We get

$$\begin{aligned} V_{o_2} &= \left(1 + \frac{R_f}{R}\right) V_2 \left(\frac{R_b}{R + R_b}\right) \\ &= \left(\frac{R + R_b}{R}\right) V_2 \left(\frac{R_b}{R + R_b}\right) \end{aligned}$$

$$V_{o_2} = \frac{R_b}{R} V_2 - (17)$$

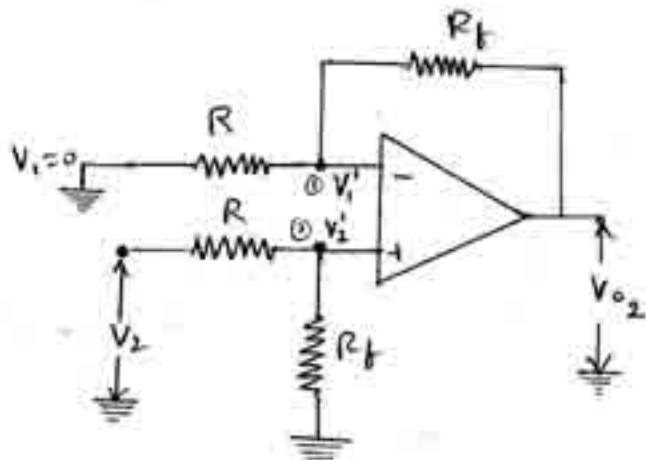
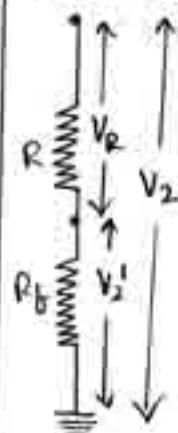


Fig *:

Voltage @ Potential division rule



Voltage across R_b ,

$$V_2' = V_2 \times \frac{R_b}{R + R_b}$$

Voltage across R ,

$$V_R = V_2 \frac{R}{R + R_b}$$

From Superposition theorem, the output voltage is

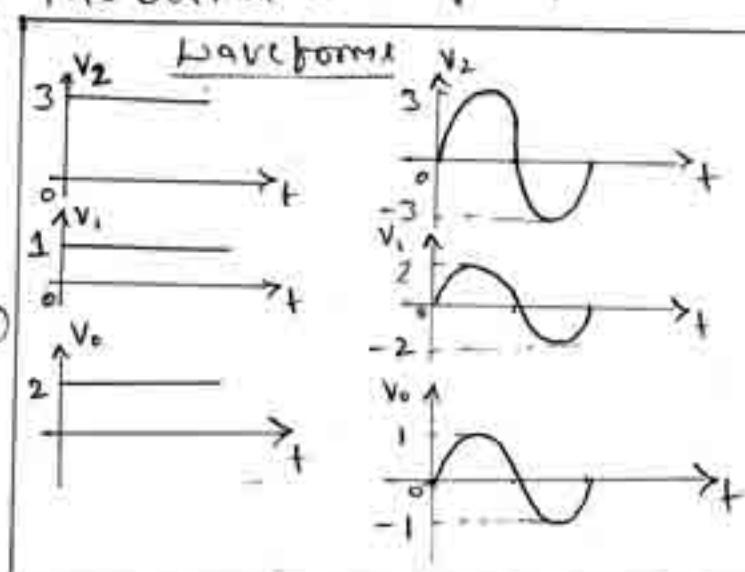
$$V_o = V_{o_1} + V_{o_2}$$

$$= -\frac{R_b}{R} V_1 + \frac{R_b}{R} V_2$$

$$V_o = \frac{R_b}{R} (V_2 - V_1) - (18)$$

If $R = R_b$, then

$$V_o = V_2 - V_1 - (19)$$

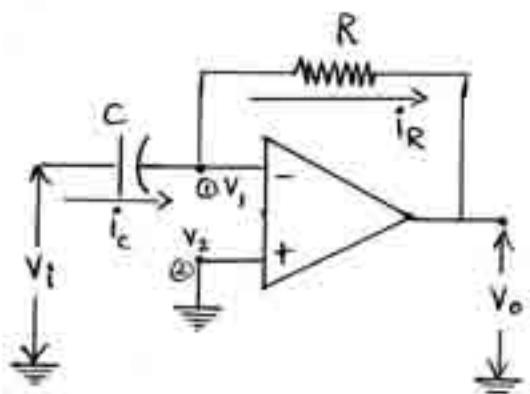


Conclusion: From (13) & (19), the output voltage is the difference of the two input voltages.

* ⑥ Differentiator:

Definition: An op-amp circuit, in which the output voltage is the differentiation (derivative) of the input voltage is called differentiator.

Circuit diagram



Analytic:

APPLYING KCL at node D.

$$i_c = i_R$$

$$C \frac{d(V_i - V_1)}{dt} = \frac{V_i - V_1}{R}$$

$$\Rightarrow C \frac{dV_i}{dt} = -\frac{V_o}{R} \quad (\because \text{From virtual ground concept}, V_1 = V_2 = 0)$$

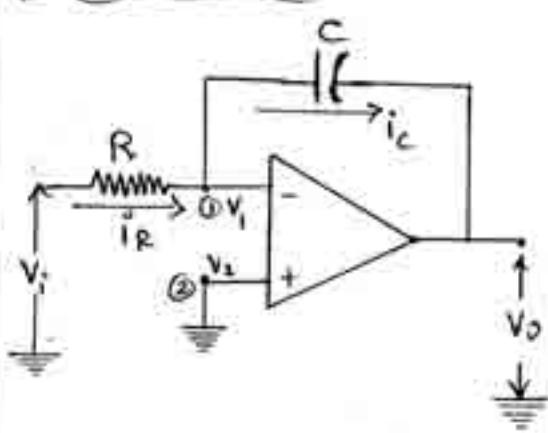
$$\Rightarrow V_o = -RC \frac{dV_i}{dt} \quad \boxed{\text{---(20)}}$$

Conclusion: From (20), the output voltage is proportional to the time derivative of the input voltage.

* ⑦ Integrator:

Definition: An op-amp circuit, in which the output voltage is the integration of the input voltage is called integrator.

Circuit diagram:



Analytic:

APPLYING KCL at node D.

$$i_R = i_C$$

$$\frac{V_i - V_1}{R} = C \frac{d(V_1 - V_o)}{dt}$$

$$\Rightarrow \frac{V_i}{R} = -C \frac{dV_o}{dt} \quad (\text{From virtual ground concept, } V_1 = V_2 = 0)$$

$$\Rightarrow dV_o = -\frac{1}{RC} V_i dt$$

Integrating on b.s.

$$V_o = -\frac{1}{RC} \int_0^t V_i dt + V_o(0) \quad -①$$

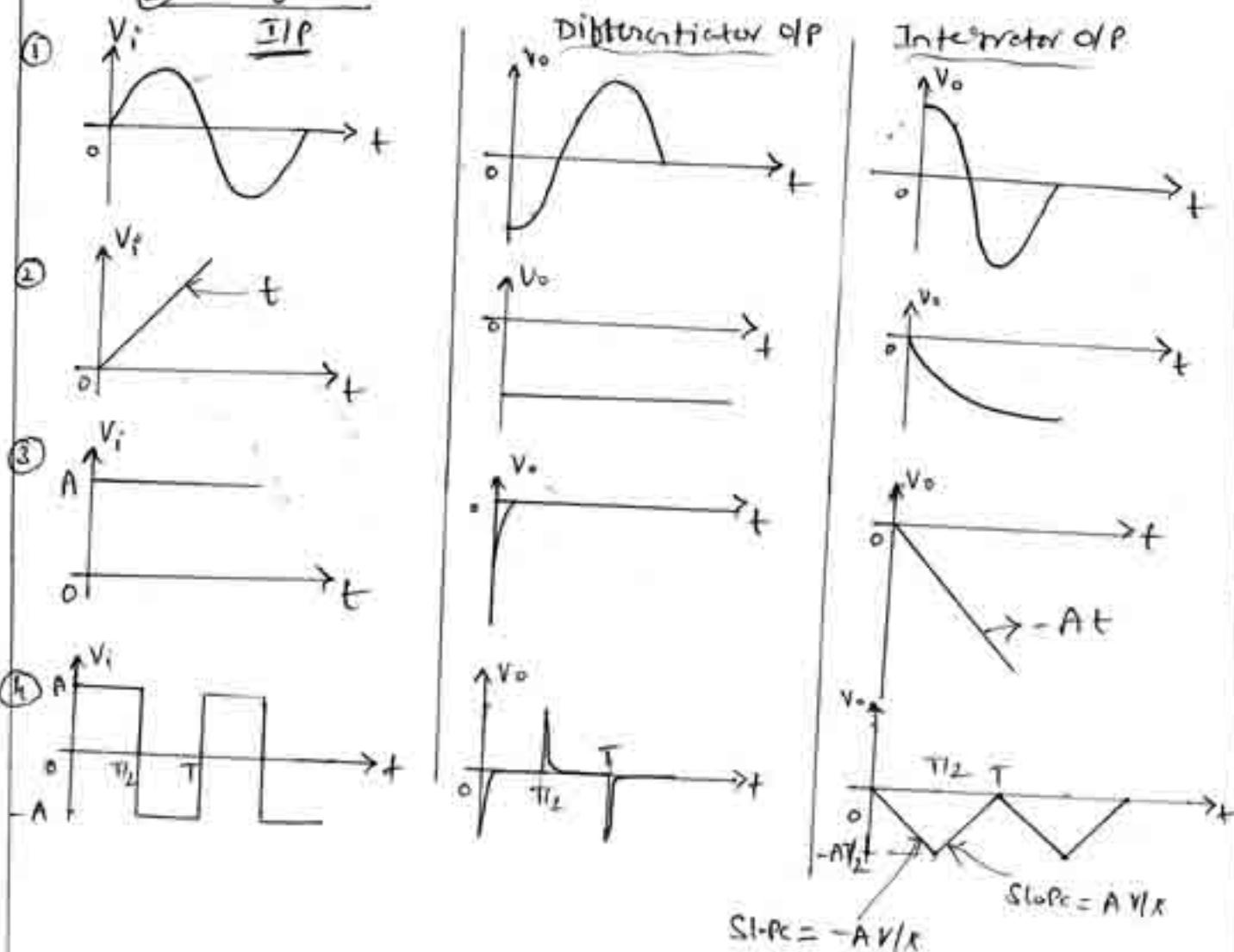
Where. $V_o(0) \rightarrow$ Initial Voltage on Capacitor at $t=0$
 (constant of integration)

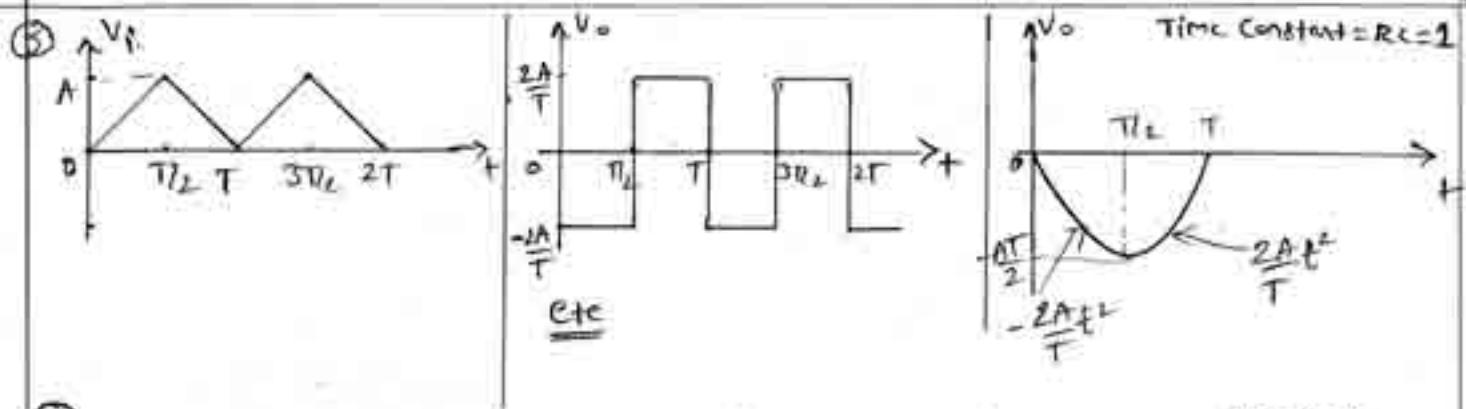
If $V_o(0)=0$, then

$$V_o = -\frac{1}{RC} \int_0^t V_i dt \quad -②$$

Conclusion: From ① @ ②, the output voltage is proportional to the integral of the input voltage.

Note: ① Waveforms



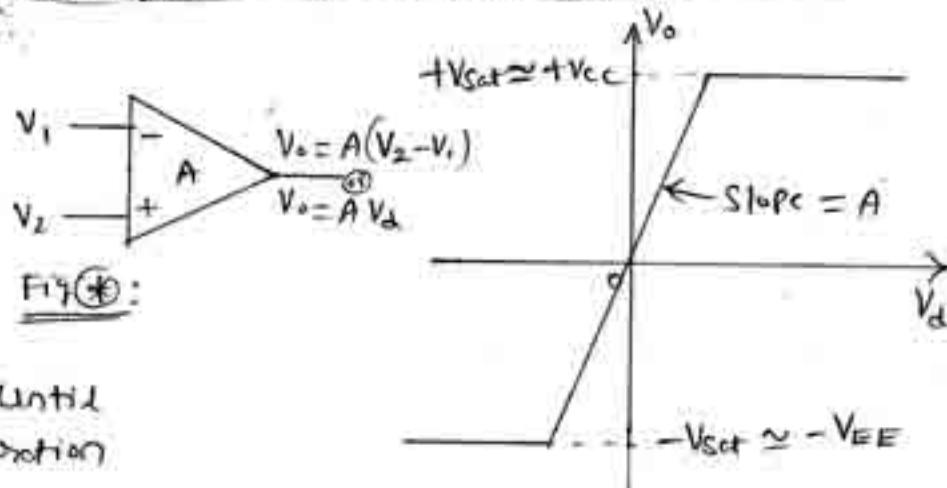


II Ideal Voltage transfer characteristic of an OP-amp

The output voltage,
 $V_o = A V_d$

For characteristic

- As V_d increases,
 V_o increases linearly until it attains the saturation voltage & thereafter it remains constant.



Fig*: Ideal voltage transfer characteristic of an OP-amp

III Need for an OP-amp

Let two signals V_1 & V_2 to be summed at node A in Fig***

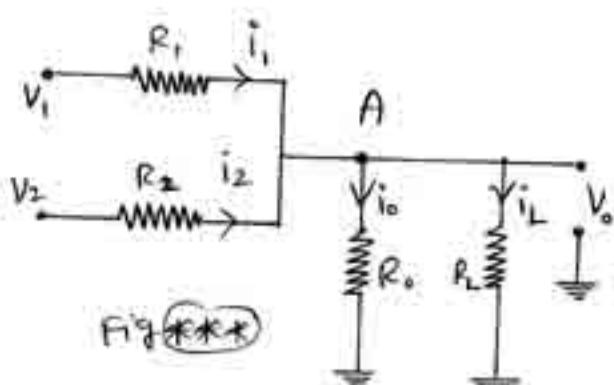
Applying KCL at node A

$$i_1 + i_2 = i_o + i_L$$

$$\Rightarrow \frac{V_1 - V_o}{R_1} + \frac{V_2 - V_o}{R_2} = \frac{V_o}{R_o} + \frac{V_o}{R_L}$$

$$\Rightarrow \frac{V_1}{R_1} + \frac{V_2}{R_2} = V_o \left[\frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_o} + \frac{1}{R_L} \right]$$

$$\Rightarrow V_o \left[\frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_o} \right] = \frac{V_1}{R_1} + \frac{V_2}{R_2}$$



$$\Rightarrow V_o \left[1 + \frac{R_p}{R_1} + \frac{R_p}{R_2} \right] = V_1 \left(\frac{R_p}{R_1} \right) + V_2 \left(\frac{R_p}{R_1} \right) \quad \text{[where } R_p = \frac{1}{R_o} + \frac{1}{R_L} \text{]}$$

$$\Rightarrow V_o = \frac{V_1 \left(\frac{R_p}{R_1} \right) + V_2 \left(\frac{R_p}{R_1} \right)}{\left[1 + \frac{R_p}{R_1} + \frac{R_p}{R_2} \right]} \quad \rightarrow \star$$

From eqn \star , it is clear that V_o depends on R_p which in turn depends on R_L .

It is desirable to make V_o independent of R_L . This is possible if $R_o \ll R_L @ \frac{1}{R_o} \gg \frac{1}{R_L}$ ($R_p \approx \frac{1}{R_o}$)

But R_p will be small, \Rightarrow small value of V_o which is undesirable. Therefore it is necessary to use amplifiers whose gain (@ output voltage) is independent of R_L .

Thus op-amp is preferred since closed-loop voltage gain (@ output voltage) is independent of R_L (depends only on external resistors R_f & R_i).

- ① For an inverting amplifier $R = 10\text{ k}\Omega$ & $R_f = 60\text{ k}\Omega$.
What is the output voltage for $V_i = 2\text{ V}$?

Sol: Given $R = 10\text{ k}\Omega$, $R_f = 60\text{ k}\Omega$, $V_i = 2\text{ V}$, $V_o = ?$

For an inverting amplifier,

$$V_o = -\frac{R_f}{R} V_i = -\frac{60 \times 10^3}{10 \times 10^3} (2) = \underline{\underline{-12\text{ V}}}$$

- ② Design an inverting amplifier for output voltage of -10 V & an input voltage of 1 V .

Sol: Given $V_o = -10\text{ V}$, $V_i = 1\text{ V}$, $R_i = ?$, $R_f = ?$

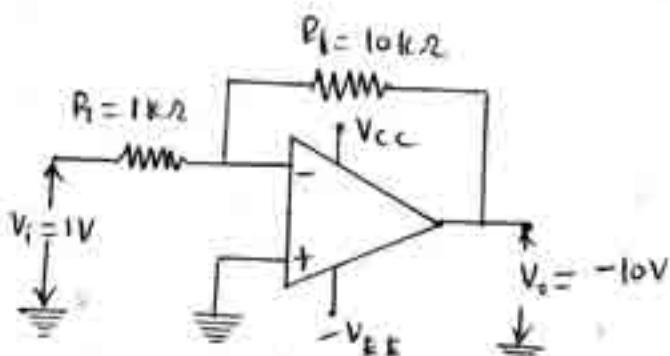
For an inverting amplifier,

$$V_o = -\frac{R_f}{R_i} V_i$$

$$\Rightarrow -10 = -\frac{R_f}{R_i}(1)$$

$$\Rightarrow \frac{R_f}{R_i} = 10$$

Assume $R_i = 1\text{ k}\Omega$ //



$$\therefore R_f = 10\text{ k}\Omega //$$

- ③ The output signal of an OP-amp with a slew-rate of $5\text{ V}/\mu\text{s}$ has a maximum value of 15 V . Find the max freq for undistorted output voltage.

Sol: Given $SR = 5\text{ V}/\mu\text{s}$: $V_m = 15\text{ V}$, $f_{max}(\text{Hz}) = ?$

$$\begin{aligned} \text{We have } f_{max} &= \frac{SR}{2\pi V_m} & \omega_{max} &= \frac{SR}{V_m} \\ &= \frac{5/10^{-6}}{2\pi(15)} & \omega_{max} &= \frac{5/10^{-6}}{15} \end{aligned}$$

$$f_{\text{max}} = 53.05 \text{ kHz} @ L_{\text{min}} = 333.33 \text{ nH}$$

- ④ Determine the output voltage of an op-amp for the input voltages of $0.05 \text{ mV} \leq 0.04 \text{ mV}$. The differential gain of the amplifier is 50000 & $\text{CMRR} = 2 \times 10^5$.

Sol: Given $V_o = ?$, $V_1 = 0.05 \text{ mV}$, $V_2 = 0.04 \text{ mV}$, $A_d = 50000$,
 $\text{CMRR} = 2 \times 10^5$

We have,

$$V_o = A_d V_d + A_c V_c$$

$$= 50000 \times 10 \times 10^{-6} + 0.25 \times 10^{-5} \times 10^{-6}$$

$$= 0.5 + 11.25 \times 10^{-6}$$

$$= 500.011 \text{ mV}$$

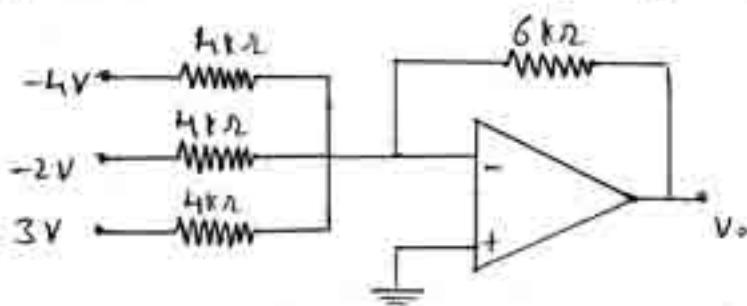
$$\therefore V_d = V_1 - V_2$$

$$= 0.05 \times 10^{-3} - 0.04 \times 10^{-3}$$

$$= 0.01 \times 10^{-3} = 10 \times 10^{-6}$$

$$A_c = \frac{A_d}{\text{CMRR}} = \frac{50000}{2 \times 10^5} = 0.25$$

- ⑤ Find the output voltage for the circuit shown in fig ⑤



sol:

We have, $V_o = -\left(\frac{R_f}{R_1} V_1 + \frac{R_f}{R_2} V_2 + \frac{R_f}{R_3} V_3\right)$

$$= -\frac{R_f}{R_1} (V_1 + V_2 + V_3) \quad (\because R_1 = R_2 = R_3 = 4k\Omega)$$

$$= -\frac{6k\Omega}{4k\Omega} (-4 - 2 + 3)$$

$$= \underline{\underline{4.5V}}$$

(3)

6) Design an adder circuit for $V_o = -[2V_1 + 3V_2 + 5V_3]$

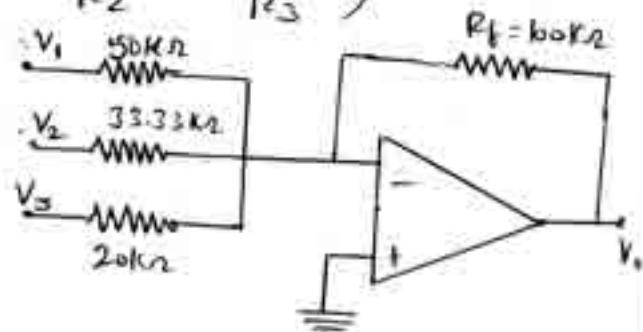
Given $V_o = -(2V_1 + 3V_2 + 5V_3)$

Comparing with $V_o = -\left(\frac{R_f}{R_1}V_1 + \frac{R_f}{R_2}V_2 + \frac{R_f}{R_3}V_3\right)$

$$\frac{R_f}{R_1} = 2, \quad \frac{R_f}{R_2} = 3, \quad \frac{R_f}{R_3} = 5$$

Let $R_f = 100\text{k}\Omega$

$$\therefore R_1 = \frac{R_f}{2}, \quad R_2 = \frac{R_f}{3}, \quad R_3 = \frac{R_f}{5}$$



$$\Rightarrow R_1 = 50\text{k}\Omega, \quad R_2 = 33.33\text{k}\Omega, \quad R_3 = 20\text{k}\Omega$$

7) Design an adder circuit for $V_o = 3V_1 + 2V_2 - 4V_3$

Given $V_o = 3V_1 + 2V_2 - 4V_3$

$$\Rightarrow V_o = -[3(-V_1) + 2(-V_2) + 4V_3]$$

Comparing with

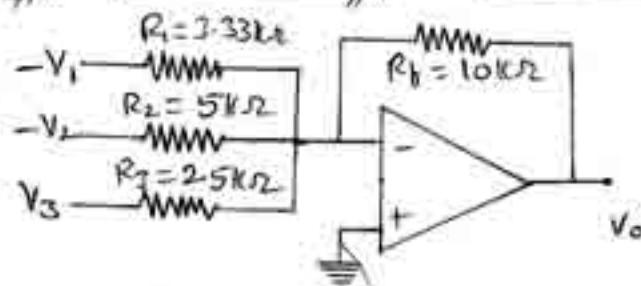
$$V_o = -\left[\frac{R_f}{R_1}(-V_1) + \frac{R_f}{R_2}(-V_2) + \frac{R_f}{R_3}V_3\right]$$

$$\frac{R_f}{R_1} = 3, \quad \frac{R_f}{R_2} = 2, \quad \frac{R_f}{R_3} = 4$$

Let $R_f = 10\text{k}\Omega$

$$\therefore R_1 = \frac{10\text{k}}{3}, \quad R_2 = \frac{10\text{k}}{2}, \quad R_3 = \frac{10\text{k}}{4}$$

$$R_1 = 3.33\text{k}\Omega // \quad R_2 = 5\text{k}\Omega // \quad R_3 = 2.5\text{k}\Omega //$$



- ③ A differential amplifier has open circuit gain of 10^4 , the input signals are $1.2 \text{ mV} \leq 2.4 \text{ mV}$. Determine the output voltage.

Sol: Given $A_d = 10^4$, $V_2 = 2.4 \times 10^{-6} \text{ V}$, $V_1 = 1.2 \times 10^{-6} \text{ V}$, $V_o = ?$

Output Voltage, $V_o = A_d V_d$

$$= A_d(V_2 - V_1) \quad (\because \text{since AC it is not given})$$

$$= 10^4(2.4 - 1.2) \times 10^{-6}$$

$$= \underline{\underline{0.012 \text{ V}}}$$

- ④ For the circuit shown in fig ①, draw the output voltage for the input voltage shown in fig ①

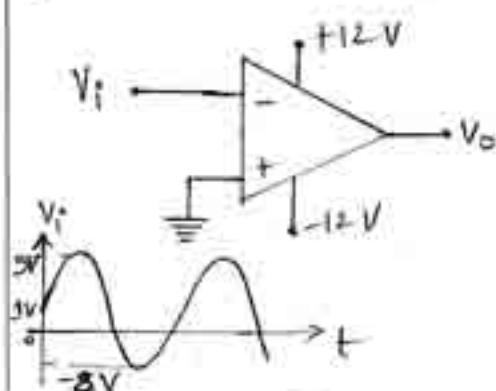


Fig 19(a)

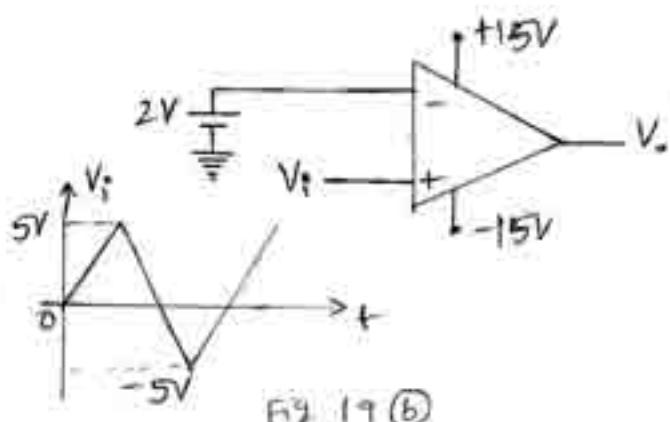
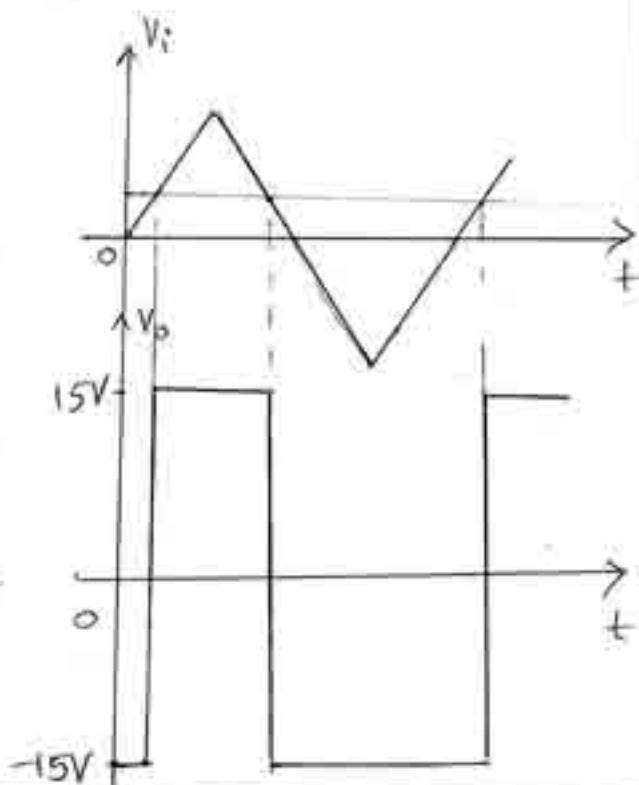
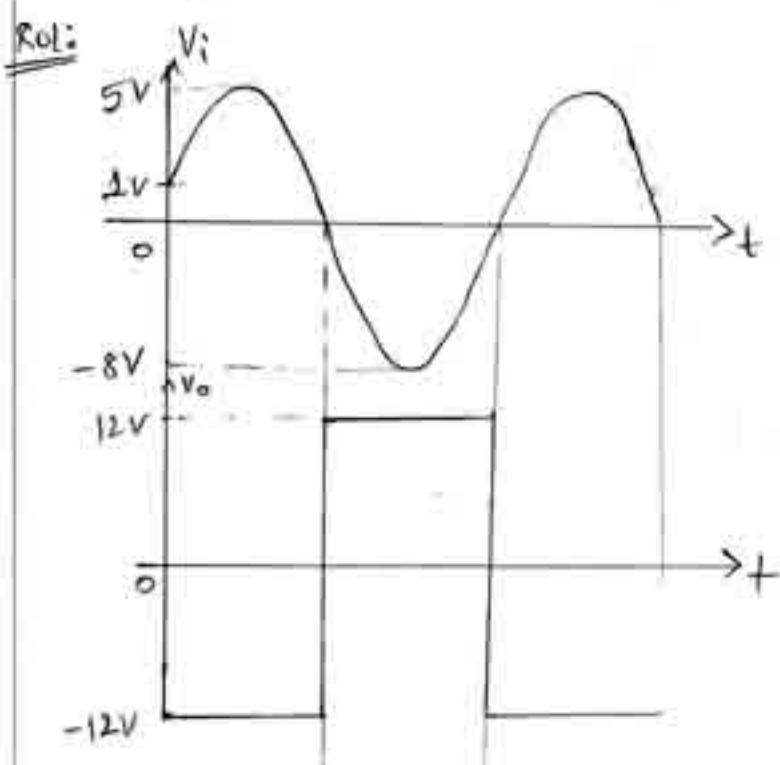


Fig 19(b)



⑩ Calculate the CMRR for the circuit measurements shown in fig ⑩.

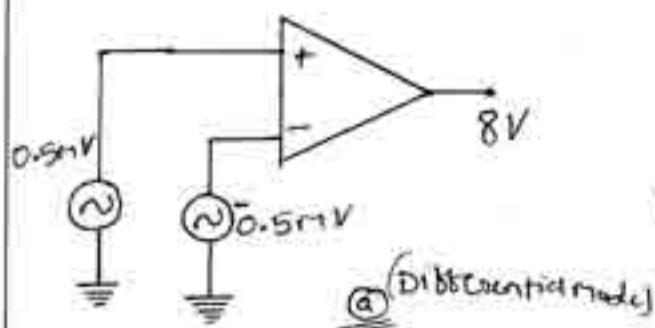
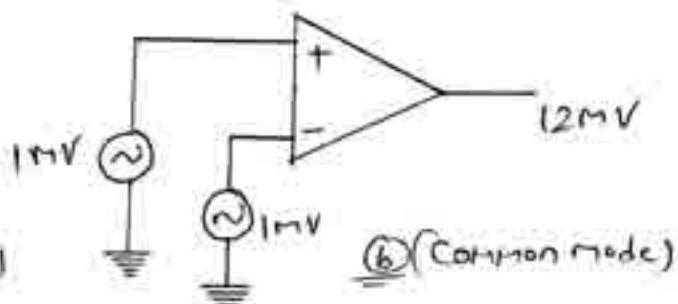


Fig 10@



⑥ (Common mode)

Rul: Fig 10@ can be redrawn as shown in fig 11@ & fig 10@ can be redrawn as shown in fig 11@.

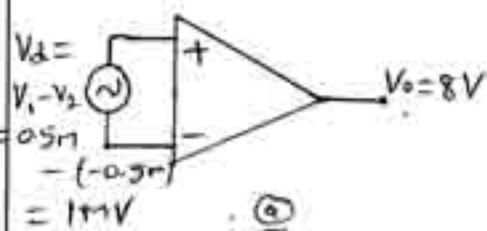
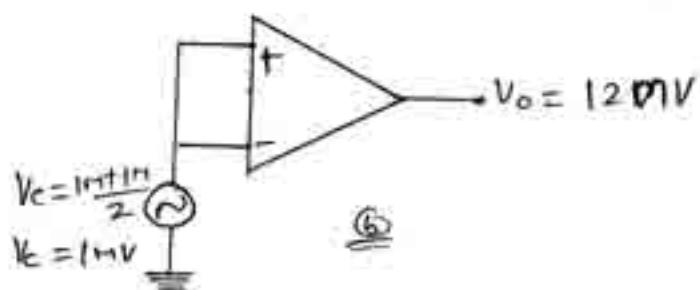


Fig 11@



From fig 10@,

$$A_d = \frac{V_o}{V_d} = \frac{8}{1 \times 10^{-3}} = 8000$$

From fig 10@,

$$A_c = \frac{V_o}{V_c} = \frac{12}{1 \times 10^{-3}} = 12000$$

∴ CMRR is,

$$\text{CMRR} = \frac{A_d}{A_c} = \frac{8000}{12} = 666.66$$

⑥

$$\text{CMRR (dB)} = 20 \log_{10} \frac{A_d}{A_c} = 20 \log_{10} (666.66) = 56.47 \text{ dB}$$

⑪ Determine the output voltage of an op-amp for input voltages of $V_{i1} = 150 \text{ mV}$, $V_{i2} = 140 \text{ mV}$. The amplifier has a differential gain of $A_d = 4000$ & the value of CMRR is:

⑤ 100 ⑥ 105.

Rul: Difference voltage, $V_d = V_{i1} - V_{i2} = 150 \times 10^{-3} - 140 \times 10^{-3} = 10 \text{ mV}$

Common mode voltage, $V_c = \frac{V_{i1} + V_{i2}}{2} = \frac{150 \times 10^{-3} + 140 \times 10^{-3}}{2} = 145 \text{ mV}$

Ques have. $V_o = A_d V_d \left(1 + \frac{1}{CMRR} \frac{V_c}{V_d}\right)$

$$= (4000) (10 \times 10^{-6}) \left(1 + \frac{1}{100} \frac{14.5 \times 10^{-6}}{10 \times 10^{-6}}\right)$$

$$= 40 \times 10^{-3} (1 + 0.145)$$

$$= \underline{\underline{4.58 \text{ mV}}}$$

(b) $V_o = (4000) (10 \times 10^{-6}) \left(1 + \frac{1}{10^5} \frac{14.5 \times 10^{-6}}{10 \times 10^{-6}}\right)$

$$= 40 \times 10^{-3} (1.000145)$$

$$= \underline{\underline{40.0058 \text{ mV}}}$$

12) Calculate the output voltage of a non-inverting amplifier

for $V_i = 2V$, $R_f = 500 \text{ k}\Omega$ & $R_i = 100 \text{ k}\Omega$

Ans: Given $V_i = 2V$, $R_f = 500 \text{ k}\Omega$, $R_i = 100 \text{ k}\Omega$, $V_o = ?$

For non-inverting amplifier,

$$V_o = \left(1 + \frac{R_f}{R_i}\right) V_i = \left(1 + \frac{500 \times 10^3}{100 \times 10^3}\right) 2 = 8(2) = \underline{\underline{12V}}$$

13) A 741C is an OP-AMP with $A = 100,000$ & a minimum CMRR dB = 70 dB. What is the common-mode voltage gain? If a desired common-mode signal each has a value of 5mV, what is the output voltage?

Ans: Given $A = A_d = 100,000$, $CMRR(dB) = 70 \text{ dB}$, $A_c = ?$

$$V_c = 5 \times 10^{-3} \text{ V}, V_o = ?$$

We have $CMRR(dB) = 20 \log_{10} \frac{A}{A_c}$

$$\Rightarrow 70 = 20 \log_{10} \frac{A}{A_c}$$

$$\Rightarrow \frac{A}{A_c} = 10^{70/20}$$

$$\Rightarrow A_c = \frac{A}{10^{70/20}} = \frac{100,000}{10^{70/20}} = \underline{\underline{31.622}}$$

We have

$$\begin{aligned} V_o(\text{cm}) &= A_c V_c \\ &= 31.622 \times 5 \times 10^6 \end{aligned}$$

$$\underline{V_o(\text{cm}) = 158.11 \text{ mV}}$$

- (b) Assume that negative saturation occurs at 1V less than the supply voltage with an OP-AMP. How much inverting input voltage does it take to drive the OP-AMP of fig (a) into negative saturation?

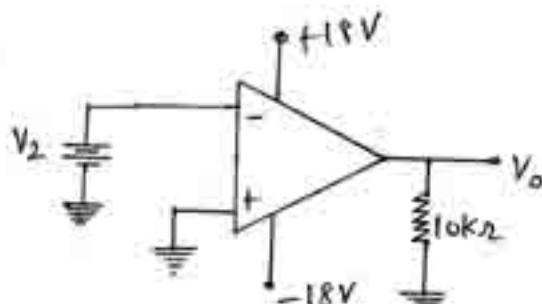


Fig (a)

RQ: Given $V_{cc} = \pm 18V$, Negative saturation voltage = -17V
 $V_2 = ?$ $A = 2 \times 10^5$ (Assume)

Given negative saturation voltage = -17V, Output saturates negatively at -17V.

$$\therefore V_2 = \frac{17}{200,000} = \underline{\underline{85 \text{ mV}}} \quad [\because V_o = A V_2]$$

- (c) The input voltage to an OP-AMP is a large voltage step. The output is an exponential waveform that changes 0.75V in 5ms. What is the slew rate of the OP-amp?

RQ: Given $dV = 0.75V$, $dt = 5\text{ms}$

We have, $SR = \frac{dV}{dt} = \frac{0.75}{5 \times 10^{-3}} = \underline{\underline{15 \text{ V/}\mu\text{s}}}$

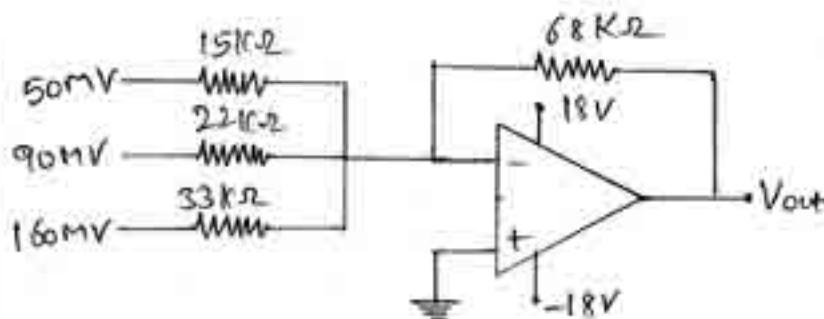
- (d) An OP-AMP has slew rate of 8V/μs. What is the power bandwidth for a peak output voltage of 5V?

RQ: Given $SR = 8 \text{ V}/\mu\text{s}$, $V_m = 5 \text{ V}$, $f_{max} = ?$

Highest free power bandwidth,

$$f_{\text{max}} = \frac{SR}{2\pi V_m} = \frac{8/10^6}{2\pi \times 5} = 254.64 \text{ kHz}$$

- 17) In fig (7). What is the ac output voltage? If a compensating resistor needs to be added to non-inverting input, what size should it be?



Ans:

Ac output voltage,

$$\begin{aligned} V_o &= \left(\frac{R_f}{R_1} V_1 + \frac{R_f}{R_2} V_2 + \frac{R_f}{R_3} V_3 \right) \\ &= \left[\frac{68k}{15k} (50 \times 10^{-3}) + \frac{68k}{22k} (90 \times 10^{-3}) + \frac{68k}{33k} (160 \times 10^{-3}) \right] \\ &= \underline{\underline{834.53 \text{ mV}}} \end{aligned}$$

Compensating resistor,

$$\begin{aligned} R_C &= R_1 \parallel R_2 \parallel R_3 \\ &= \frac{1}{\frac{1}{15k} + \frac{1}{22k} + \frac{1}{33k}} \\ &= \underline{\underline{7.02 \text{ k}\Omega}} \end{aligned}$$

If a summing circuit needs to be compensated by adding an equal resistance to the non-inverting input, the resistance is the Thevenin resistance looking from the inverting input back to the source.

- 18) What is the initial slope of a sine wave with a frequency of 15kHz & a peak value of 2V? What happens to the initial slope if the frequency increases to 30kHz?

Rul: Given @ $f = 15 \text{ kHz}$, $V_m = 2V$, $S_s(SR) = ?$

Initial slope of a sine wave.

$$S_s = 2\pi f V_m \quad (\because SR = S_s = 2\pi f V_m)$$

$$= 2\pi \times 15 \times 10^3 \times 2$$

$$= 188.49 \text{ mV/Hz}$$

b) $f = 30 \text{ kHz}$, $V_m = 2V$, $S_s = ?$

$$S_s = 2\pi f V_m = 2\pi \times 30 \times 10^3 \times 2 = 376.99 \text{ mV/Hz}$$

(d) Find V_{out}

in fig (19), if

$$R = 10k\Omega, V_1 = -20 \text{ mV}$$

$$V_2 = -20 \text{ mV}$$

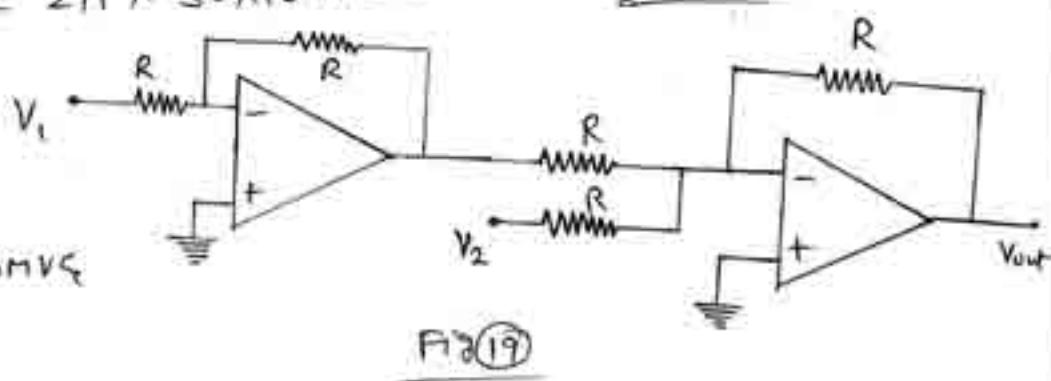
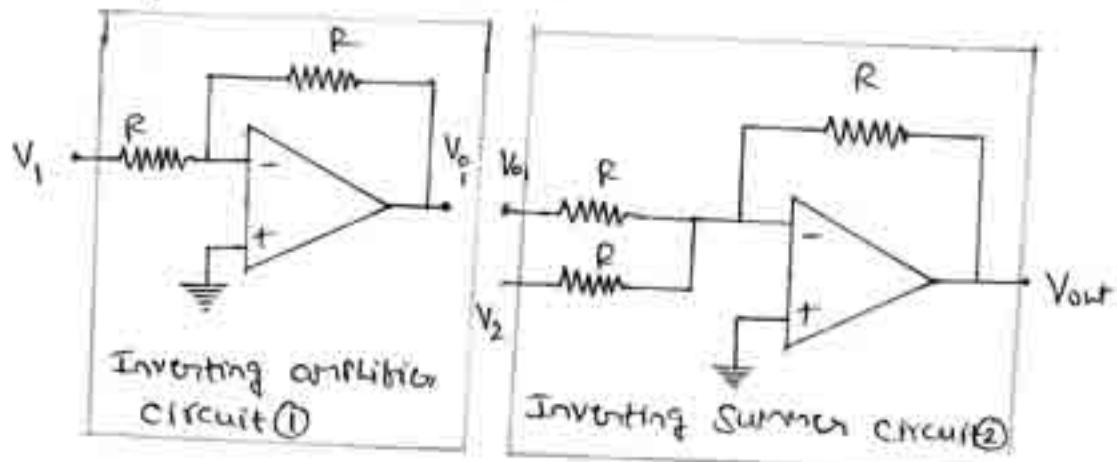


Fig 19

Rul:

The given circuit is redrawn



From circuit (1).

$$V_{01} = -\frac{R}{R} V_1$$

$$= -(-20 \text{ mV})$$

$$= 20 \text{ mV}$$

From circuit (2)

$$V_{out} = -\left(\frac{R}{R} V_{01} + \frac{R}{R} V_2\right)$$

$$= -(20 \text{ mV} - 30 \text{ mV})$$

$$= -20 \text{ mV} + 30 \text{ mV}$$

$$V_{out} = \underline{10 \text{ mV}}$$

The given circuit is a subtractor

d) In the OP-AMP circuit of Fig 20. Show that $V_o = (V_3 + V_4) - (V_1 + V_2)$ if all resistances are equal.

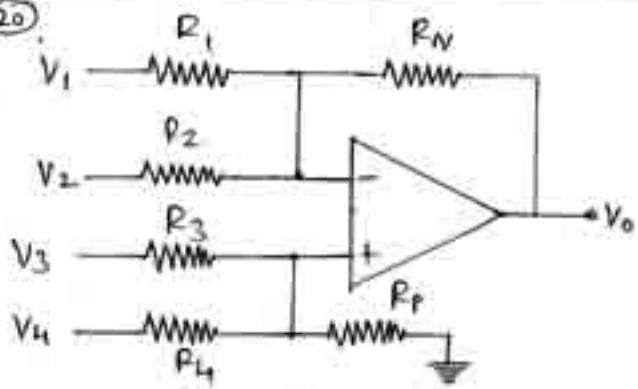


Fig 20

Rd:

Let us use superposition theorem.

case(i): Let $V_2 = V_3 = V_4 = 0$

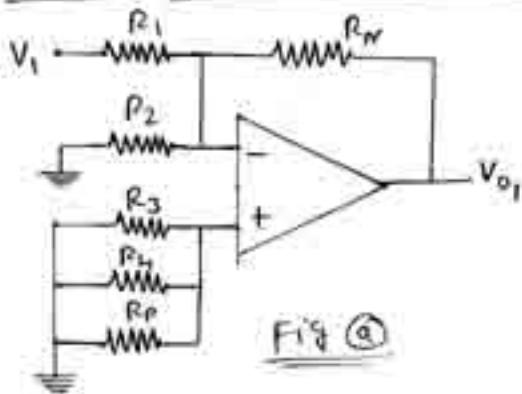


Fig (a)

The resulting circuit is shown in Fig (a). The circuit is an inverting amplifier. Of V1 is,

$$\therefore V_{o1} = -\frac{R_f}{R_1} V_1$$

$$V_{o1} = -V_1 \quad (\text{Let } R_1 = R_f)$$

case(ii): Let $V_1 = V_2 = V_4 = 0$

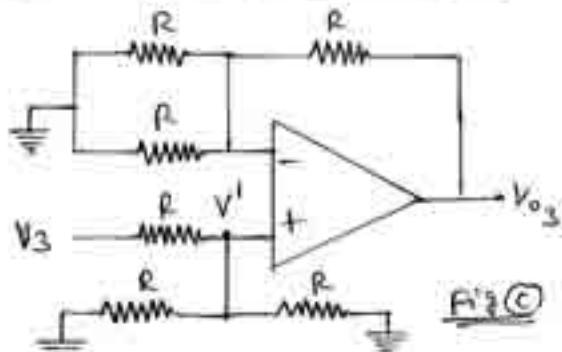


Fig (b)

From potential divider rule,

$$V' = \frac{V_3 (R || R)}{R + (R || R)}$$

case(iii): Let $V_1 = V_3 = V_4 = 0$

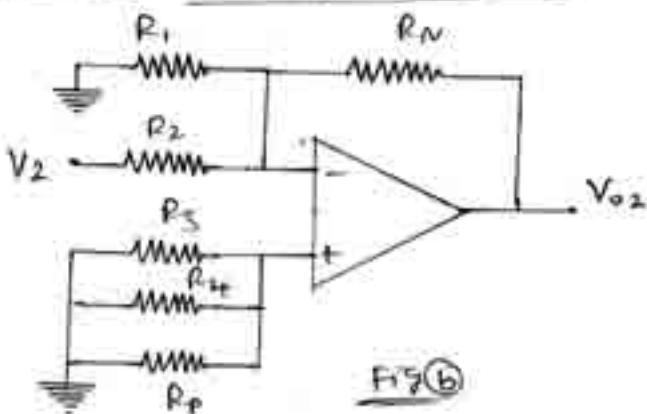


Fig (c)

The output voltage V_{o2} is,

$$V_{o2} = -\frac{R_f}{R_2} V_2$$

$$V_{o2} = -V_2 \quad (\text{Let } R_2 = R_f)$$

case(iv): Let $V_1 = V_2 = V_3 = 0$

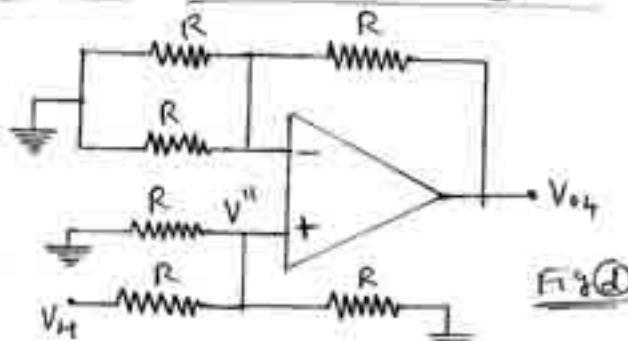


Fig (d)

From potential divider rule,

$$V'' = \frac{V_4 (R || R)}{R + (R || R)}$$

$$V' = V_3 \frac{RR}{R+R}$$

$$= \frac{V_3 \frac{RR}{R+R}}{R + \frac{RR}{R+R}}$$

$$= V_3 \frac{R^2}{2R}$$

$$= \frac{V_3 R^2}{2R + R^2}$$

$$= V_3 \frac{R^2}{3R + R}$$

$$= \frac{V_3}{3} - \textcircled{*}$$

Now Fig (c) can be redrawn as

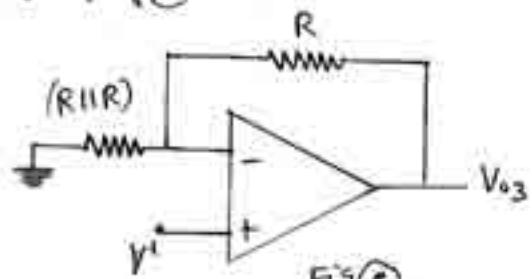


Fig (c)

The resulting circuit shown in Fig (c) is non-inverting amplifier.

∴ The output voltage V_{o3} is

$$V_{o3} = \left[1 + \frac{R}{(R||R)} \right] V' - \textcircled{****}$$

using $\textcircled{*}$ in $\textcircled{****}$,

$$V_{o3} = \left[1 + \frac{R}{(RR/R+R)} \right] \frac{V_2}{3}$$

$$= \left(1 + \frac{R}{R^2/2R} \right) \frac{V_2}{3}$$

$$= \left(1 + 2 \right) \frac{V_2}{3}$$

$$V_{o3} = V_2 - \textcircled{3}$$

From Superposition theorem, the output voltage is

$$V_o = V_{o1} + V_{o2} + V_{o3} + V_{o4} = (V_3 + V_4) - \underline{(V_1 + V_2)}$$

$$\Rightarrow V'' = V_4 \frac{RF/R+R}{R + (RF/R+R)}$$

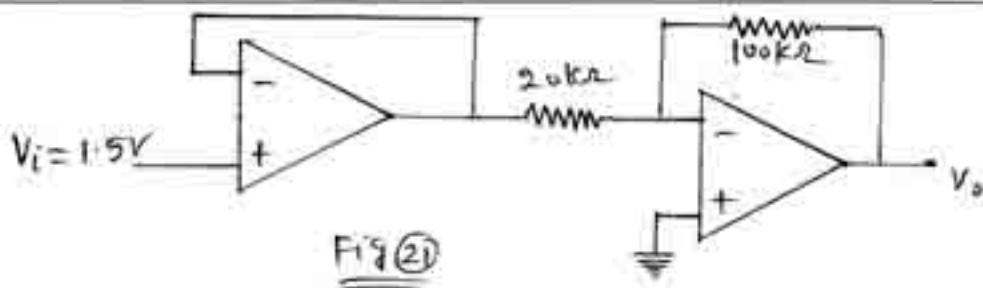
$$\Rightarrow V'' = \frac{V_4}{3} - \textcircled{**}$$

III¹⁴

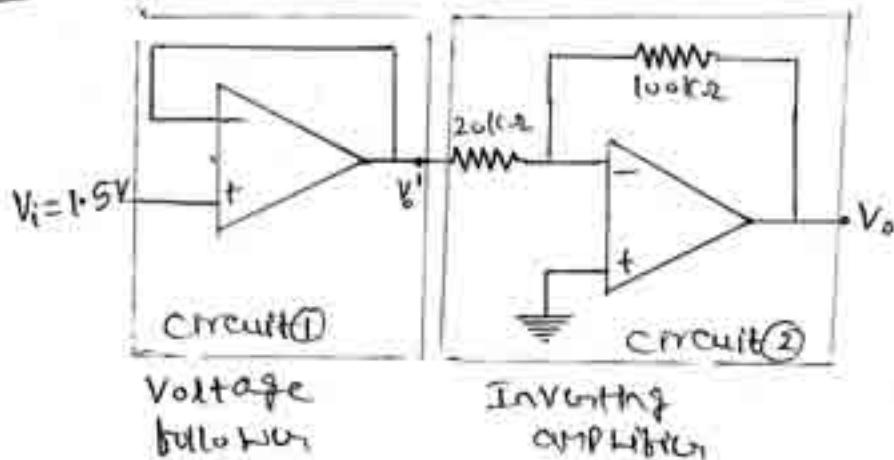
$$V_{o4} = \left[1 + \frac{R}{(R||R)} \right] V''$$

$$V_{o4} = V_4 - \textcircled{4}$$

- 3) For the bfig(2), determine V_o .



Rul:



From circuit ①, o/p of Voltage follower is,

$$V_o' = V_i = 1.5V$$

From circuit ②, output V_o is,

$$V_o = -\left(\frac{100K}{20K}\right)V_o' = -5(1.5) = \underline{\underline{-7.5V}}$$

- 2) Determine the input bias current and input Offset current to an op-amp if the current into non-inverting and inverting terminals are 8.3mA and 7.9mA respectively.

Rul: Given $I_1 = 8.3\text{mA}$, $I_2 = 7.9\text{mA}$, $I_{ib} = ?$, $I_{io} = ?$

Input bias current, $I_{ib} = \frac{I_1 + I_2}{2} = \frac{8.3 + 7.9}{2} = 8.1\text{mA}/\text//$

Input offset current, $I_{io} = |I_1 - I_2| = |8.3 - 7.9| = 0.4\text{mA}/\text//$

- 3) How long does it take the output voltage of an op-amp to go from $-8V$ to $7V$, if the slew rate is 0.5V/Ms ?

Rul: Given $dV_o = 7 - (-8) = 15\text{V}$, $SR = \frac{0.5}{10^{-6}} \text{V/s}$, $dt = ?$

We have $SR = \frac{dV_o}{dt} \Rightarrow dt = \frac{dV_o}{SR} = \frac{15}{0.5/10^{-6}} = \underline{\underline{30\mu\text{s}}}$

4) For the inverting amplifier, $R_i = 20\text{k}\Omega$, $R_f = 100\text{k}\Omega$ & $V_{in} = 1\text{mV}$, calculate

- (a) closed-loop gain (b) input resistance seen by source
- (c) output voltage (d) input current (e) current entering the op-amp input terminals (f) current through feedback

Given: $R_i = 20\text{k}\Omega$, $R_f = 100\text{k}\Omega$, $V_{in} = 1\text{mV}$, $A(A_d) = ?$.

$$R_{in} = ?, I_{in} = ?, V_o = ?, I_{op-amp} = ?, I_b = ?$$

(a) We have,

$$A = -\frac{R_f}{R_i} = -\frac{100 \times 10^3}{20 \times 10^3} = -5//.$$

(b) $R_{in} = R_i = \underline{20\text{k}\Omega}$

(c) Output Voltage, $V_o = +AV_{in} = -5 \times 1 \times 10^{-3} = \underline{-5\text{mV}}$

(d) $I_{in} = \frac{V_{in} - V_i}{R_i} = \frac{1 \times 10^{-3} - 0}{20 \times 10^3} = 50\text{nA} //$ [∴ From virtual ground, $V_i = V_2 = 0$]

(e) $I_{op-amp} = 0$ (∴ No current flows into op-amp input terminals)

(f) $I_b = I_{in} = \underline{50\text{nA}}$

5) A sinusoidal signal with peak value 6mV at 20kHz is applied to the input of an ideal op-amp integrator with $R = 100\text{k}\Omega$ & $C = 1\text{nF}$. Find the output voltage.

Given: $R = 100\text{k}\Omega$, $C = 1\text{nF}$, $V_m = 6\text{mV}$, $f = 20\text{kHz}$, $V_o = ?$

$$V_{in} = V_m \sin \omega t = 6 \times 10^{-3} \sin(2\pi f t) = 6 \times 10^{-3} \sin(40000\pi t)$$

Output Voltage,

$$V_o = -\frac{1}{RC} \int_{0}^{t} V_{in} dt + V_{o(0)}$$

$$= -\frac{1}{100 \times 10^3 \times 1 \times 10^{-9}} \int_{0}^{t} 6 \times 10^{-3} \sin(40000\pi t) dt$$

Assume $V_{o(0)} = 0$

Initial voltage across capacitor = 0

$$= -10 \left[(6 \times 10^{-3}) \left(\frac{-\cos(40000\pi t)}{40000\pi} \right)^t \right]$$

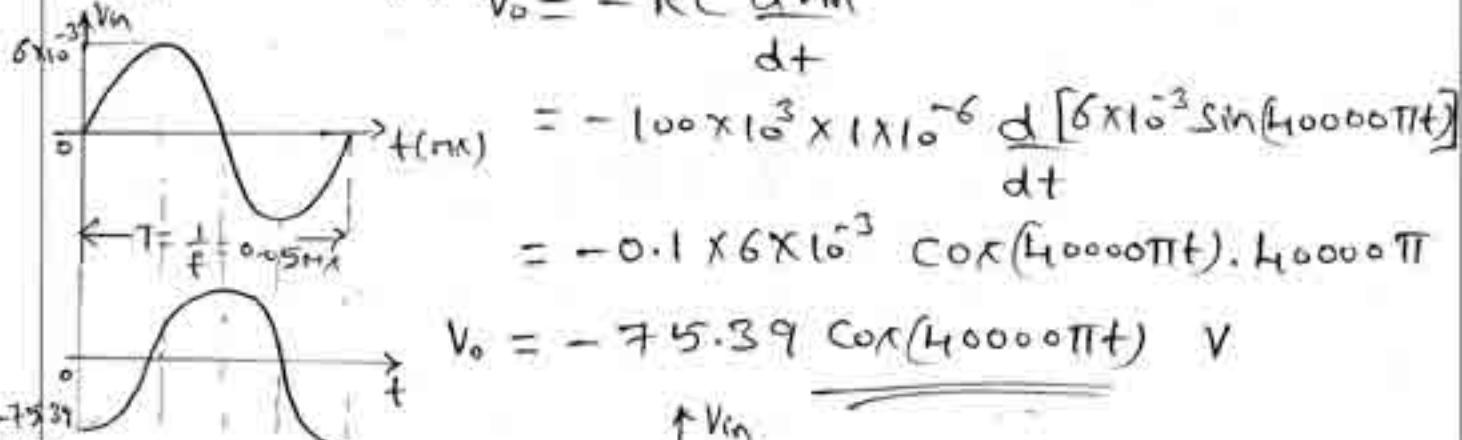
$$V_o = 477.46 [\cos(40000\pi t) - 1] \text{ mV}$$

- 26) The input to a ideal differentiator is a Sihutooidal Voltage of Peak Voltage 6MV & frequency 20 KHz. Find the output Voltage, Given $R = 100\text{ k}\Omega$ & $C = 1\text{ nF}$.

Given: Given $R = 100\text{ k}\Omega$, $C = 1\text{ nF}$, $V_m = 6\text{ MV}$, $f = 20\text{ KHz}$

$$V_{in} = V_m \sin(\omega t) = 6 \times 10^3 \sin(40000\pi t)$$

Output Voltage, $V_o = -RC \frac{dV_{in}}{dt}$



- 27) Determine the output Voltage of a ideal differentiator for the input shown in fig (27). Given $RC = 1\text{ ms}$.

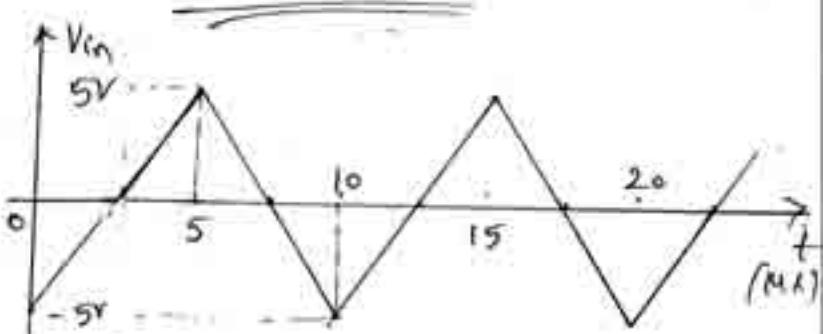


Fig (27)

Given: Given $RC = 1\text{ ms}$

case(i): For $0 < t < 5\text{ ms}$

$$\frac{dV_{in}}{dt} = \frac{15 - (-5)}{15 - 0} = 2V/\text{ms} \quad @$$

$$(x_1, y_1) \\ (5, 5)$$

$$(x_2, y_2) \\ (0, -5)$$

$$\frac{y_2 - y_1}{x_2 - x_1} = \frac{y - y_1}{x - x_1}$$

$$\Rightarrow y = 2x - 5$$

$$@ V_{in} = 2t - 5$$

$$\text{Dif-L. w.r.t } t$$

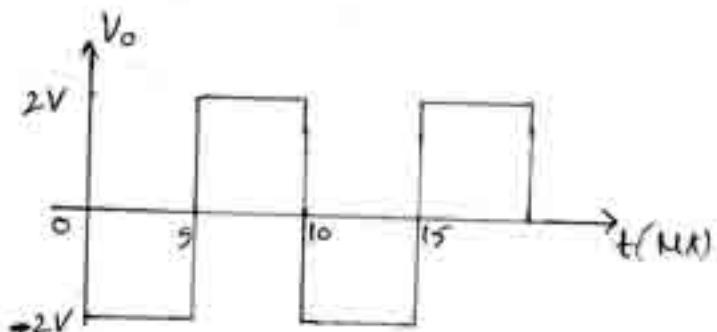
$$\frac{dV_{in}}{dt} = 2 \text{ V/ms}$$

$$\therefore V_o = -RC \frac{dV_{in}}{dt} = -1 \times 10^{-6} \frac{2}{10^{-6}} = -2V$$

Case (ii): For $5\text{m}\mu\text{s} < t < 10\text{m}\mu\text{s}$

$$\frac{dV_{in}}{dt} = \frac{-5-5}{(10-5)} = \frac{-10}{5} = -2\text{V/m}\mu\text{s}$$

$$\begin{aligned}\therefore V_o &= -RC \frac{dV_{in}}{dt} \\ &= -1 \times 10^{-6} \left(-\frac{2}{10^{-6}} \right) \\ &= \underline{\underline{2V}}\end{aligned}$$



$$\begin{aligned}y_1, y_2 \\ (5, 5) \\ (10, -5) \\ \frac{-5-5}{10-5} &= \frac{y-5}{x-5} \\ \frac{-10}{5} &= \frac{y-5}{x-5} \\ y-5 &= -2x + 10 \\ y &= -2x + 15\end{aligned}$$

$$\frac{dy}{dx} = -2\text{V/m}\mu\text{s}$$

28) Calculate

(a) The output offset voltage

due to input offset voltage =
1.2mV

(b) The output offset voltage

due to input offset current = 100nA.

(c) The output offset voltage due to input offset voltage
= 4mV & input offset current = 1.50nA.

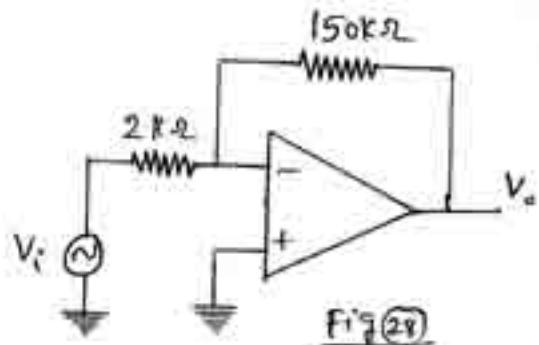


Fig 28

Ans:

(a) Given $V_{io} = 1.2\text{mV}$

Output offset voltage,

$$V_{oo}(\text{due to } V_{io}) = V_{io} \left(\frac{R_1 + R_f}{R_1} \right) = 1.2 \times 10^{-3} \left(\frac{2k + 150k}{2k} \right)$$

$$V_{oo}(\text{due to } V_{io}) = \underline{\underline{9.12\text{mV}}}$$

④ $V_{oo} (\text{due to } I_{io}) = I_{io} R_b = 100 \times 10^{-9} \times 150 \times 10^3 = 15 \text{ mV}$

⑤ $V_{oo} = V_{oo} (\text{due to } V_{io}) + V_{oo} (\text{due to } I_{io})$
 $= V_{io} \left(1 + \frac{R_f}{R_i}\right) + I_{io} R_f$
 $= 4 \times 10^{-3} \left(1 + \frac{150 \text{ k}}{2 \text{ k}}\right) + 150 \times 10^{-9} (150 \text{ k})$
 $= 304 \times 10^{-3} + 22.5 \times 10^{-3}$
 $= 326.5 \text{ mV}$

- 24) Calculate the input bias currents at each input of an OP-amp having input bias current = 30 nA & Input offset current = 5 nA

Rul:

$$\begin{aligned} \text{We have, } I_1 &= I_{ib} + \frac{I_{io}}{2} & I_2 &= I_{ib} - \frac{I_{io}}{2} \\ &= 30 \times 10^{-9} + \frac{5 \times 10^{-9}}{2} & &= 30 \times 10^{-9} - \frac{5 \times 10^{-9}}{2} \\ &= 32.5 \text{ nA} & &= 27.5 \text{ nA} \end{aligned}$$

- 25) For an op-amp having a slew rate of $2 \text{ V/}\mu\text{s}$, what is the maximum closed-loop voltage gain that can be used when the input signal varies by 0.5 V in $10 \mu\text{s}$?

Rul: We have $V_o = A V_{in}$

$$\Rightarrow dV_o = A dV_{in}$$

$$\Rightarrow \frac{dV_o}{dt} = A \frac{dV_{in}}{dt}$$

$$\Rightarrow A = \frac{\frac{dV_o}{dt}}{\frac{dV_{in}}{dt}} = \frac{SR}{dV_{in}/dt} = \frac{2/10^6}{0.5/10 \times 10^{-6}} = 40$$

Maximum closed-loop voltage gain = 40 .

- 31) For the signal & circuit of fig 31, determine the max frequency that may be used.
Op-amp Slew rate = 0.5 V/Ms .

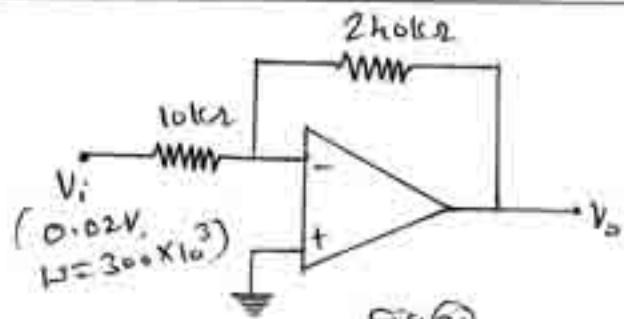


Fig 31

Rul: Gain $A = \left| \frac{R_f}{R_i} \right| = \frac{2k\Omega \times 10^3}{10 \times 10^3} = 24$

Output Voltage (maximum)

$$V_H = A V_i = 24 \times 0.02 = 0.48 \text{ V}$$

We have $\omega_m \leq \frac{SR}{V_H}$ @ $f_m \leq \frac{SR}{2\pi V_H}$
 $\leq \frac{0.5/10^6}{0.48} \leq \frac{0.5/10^6}{2\pi \times 0.48}$

$$\omega_m \leq 1.041 \times 10^6 \text{ rad/s} @ f_m \leq 165.78 \text{ kHz}$$

since the signal's frequency ($\omega = 300 \times 10^3 \text{ rad/s}$) is less than the maximum freq ω_m , no output distortion will result.

- 2) For the circuit shown in fig 32.

(a) Calculate A_1 ,

(b) Calculate A_2 ,

(c) Find the total gain

(d) Find V_o' & V_o for $V_i = A \sin \omega t (V)$

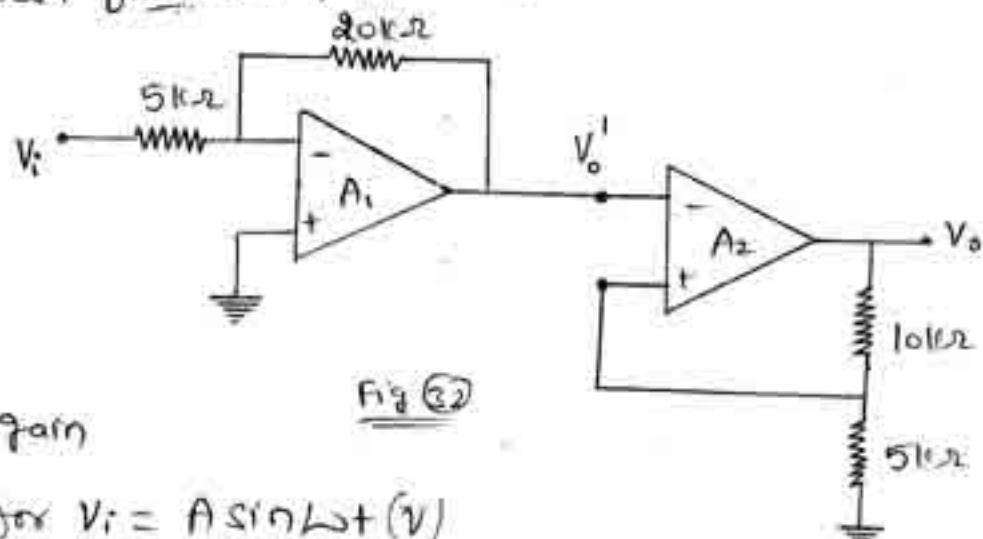


Fig 32

Rul:

(a) $A_1 = -\frac{20k\Omega}{5k} = -4$ (b) $A_2 = 1 + \frac{10k\Omega}{5k} = 3$

(c) $A = A_1 A_2 = -12$

$$\textcircled{a} \quad V_o' = (-2) A \sin \omega t = -2A \sin \omega t \text{ (V)}$$

$$\therefore V_o = A_2 V_o' = 3 (-2A \sin \omega t) = \underline{-6A \sin \omega t \text{ (V)}}$$

Q3 Design an op-amp circuit for $V_o = 2V_1 - 3V_2 + 4V_3 - 5V_4$

$$\underline{\text{Sol:}} \quad V_o = 2V_1 - 3V_2 + 4V_3 - 5V_4$$

$$\Rightarrow V_o = (2V_1 + 4V_3) - (3V_2 + 5V_4)$$

$$\boxed{V_o = V_{o1} - V_{o2}} \rightarrow \textcircled{1} \text{ where } V_{o1} = 2V_1 + 4V_3$$

$$V_{o2} = 3V_2 + 5V_4$$

$\text{Eqn } \textcircled{1}$ is the expression for output voltage of subtractor.

Consider

$$V_{o1} = 2V_1 + 4V_3$$

Comparing with,

$$V_{o1} = \frac{R_{f1}}{R_1} V_1 + \frac{R_{f1}}{R_3} V_3$$

$$\Rightarrow \frac{R_{f1}}{R_1} = 2, \quad \frac{R_{f1}}{R_3} = 4$$

$$\text{Let } R_{f1} = 100\text{k}\Omega.$$

$$\therefore R_1 = 50\text{k}\Omega, R_3 = 25\text{k}\Omega$$

Consider

$$V_{o2} = 3V_2 + 5V_4, \text{ Comparing with}$$

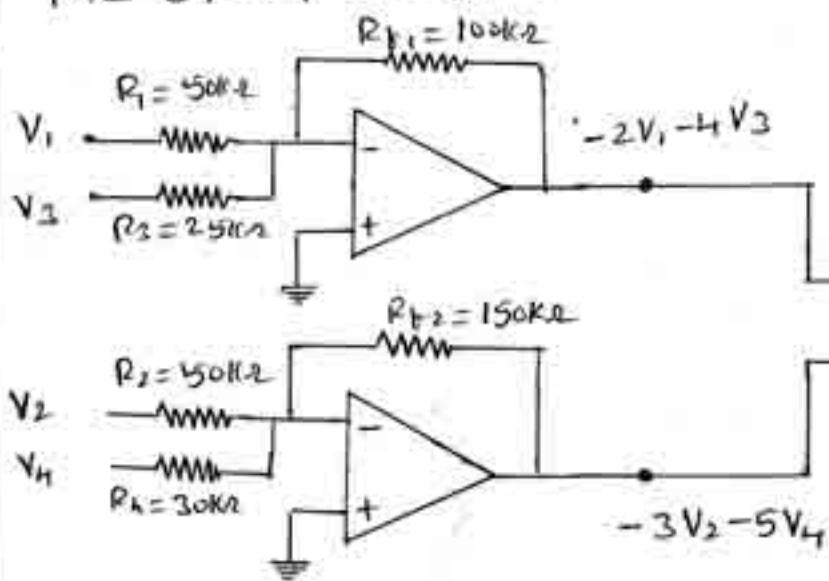
$$V_{o2} = \frac{R_{f2}}{R_2} V_2 + \frac{R_{f2}}{R_4} V_4$$

$$\Rightarrow \frac{R_{f2}}{R_2} = 3, \quad \frac{R_{f2}}{R_4} = 5$$

$$\text{Let } R_{f2} = 150\text{k}\Omega$$

$$R_2 = 50\text{k}\Omega, R_4 = 30\text{k}\Omega$$

The op-amp circuit is shown below



Let $R = 20\text{k}\Omega$

