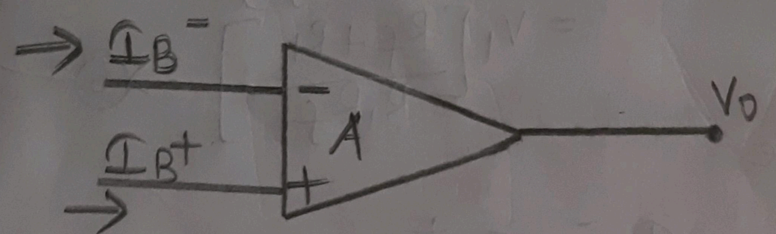
DC characteristics of op-Amp:

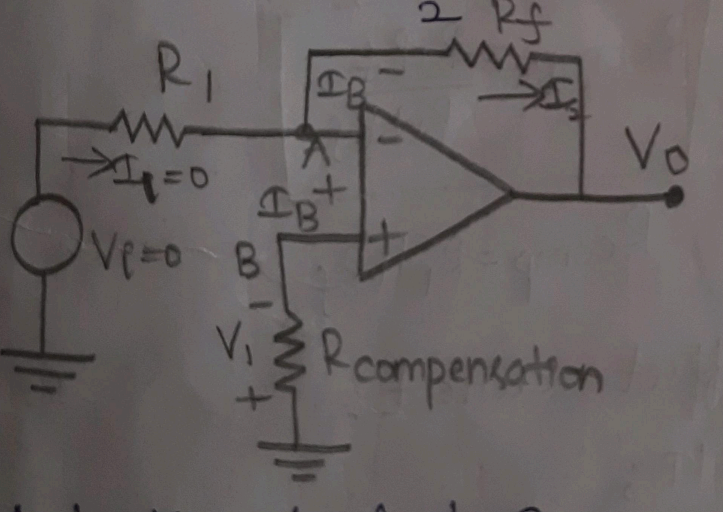
* Input bias current
* Input Offset current
* Input offset voltage
* Thermal drift

(i) Input bias current:



$I/p = 0$, $O/p = 500nA$

$$I_B = \frac{I_B^+ + I_B^-}{2} \rightarrow (1)$$



$V_0 = I_B^- \cdot R_f \rightarrow (2)$

$V_0 = V_2 - V_1$

Apply KVL to find R_{comp},

At $i/p = 0$

$$I_1 = \frac{V_1}{R_1} \; ; \; I_2 = \frac{V_2}{R_f}$$

$$V_0 = V_2 - V_1 \rightarrow (3)$$

$$V_1 = I_B^+ R_{comp} \rightarrow (4)$$

$$I_B^+ = \frac{V_1}{R_{comp}}$$

* R_{comp} ⇒ To bring o/p practically zero when i/p is zero.
* Bias current ⇓ voltage. If i/p is zero, some current will be present in o/p.
* For making that o/p as zero a R_{comp} is connected.

Assume,

$$V_2 = V_1$$

$$I_2 = \frac{V_2}{R_f}$$

$$I_2 = \frac{V_1}{R_f} \rightarrow (5)$$

KCL at node 'a',

$$I_B^- = I_1 + I_2$$

$$= \frac{V_1}{R_1} + \frac{V_1}{R_f}$$

$$I_B^- = V_1\left[\frac{1}{R_1} + \frac{1}{R_f}\right]$$

$$= V_1\left[\frac{R_f + R_1}{R_1 R_f}\right] \rightarrow (6)$$

Assume

$$I_B^- = I_B^+$$

$$V_1\left[\frac{R_1 + R_f}{R_1 R_f}\right] = \frac{V_1}{R_{comp}}$$

$$\boxed{R_{comp} = \frac{R_1 R_f}{R_1 + R_f}}$$

$$R_{comp} = R_1 \| R_f$$

(ii) Input Offset current:

We KIT,

I_B^+ ⇒ Bias current at non-inverting terminal.

I_B^- ⇒ Bias current at inverting terminal.

* There is a small difference b/w I_B^+ & I_B^- ⇒ offset current.

Rcompensation we are assuming

$$I_B^+ = I_B^-$$

Diff b/w I_B^+ & I_B^- = offset current [I_{os}]

$$|I_{OS}| = I_B^+ - I_B^-$$

We KIT,

$$V_1 = I_B^+ R_{comp} \rightarrow (7) \quad \text{[Refer eq (4)]}$$

$$I_1 = \frac{V_1}{R_1}$$

At node 'a', $[I_1 + I_2 = I_B^-]$

$$I_2 = I_B^- - I_1$$

$$= I_B^- - \frac{V_1}{R_1}$$

$$I_2 = I_B^- - \frac{I_B^+ R_{comp}}{R_1}$$

$$V_O = V_2 - V_1 \quad \text{[Refer eq (3)]}$$

$$V_2 = I_2 \cdot R_f$$

$$V_O = I_2 R_f - I_B^+ R_{comp}$$

$$V_O = \left[I_B^- - \frac{I_B^+ R_{comp}}{R_1}\right] R_f - I_B^+ R_{comp}$$

Substitute $R_{comp} = \frac{R_1 R_f}{R_1 + R_f}$,

$$V_O = \left[I_B^- - \frac{I_B^+ R_1 R_f}{R_1(R_1+R_f)}\right] R_f - I_B^+ \left(\frac{R_1 R_f}{R_1+R_f}\right)$$

$$= \frac{I_B^- R_1 R_f (R_1+R_f) - I_B^+ R_1 R_f^2 - I_B^+ R_1^2 R_f}{R_1 (R_1+R_f)}$$

$$= \frac{R_1 [I_B^- R_f (R_1+R_f) - I_B^+ R_f^2 - I_B^+ R_f R_1]}{R_1 (R_1+R_f)}$$

$$V_0 = \frac{I_B^- R_f (R_1+R_f) - I_B^+ R_f^2 - I_B^+ R_f R_1}{R_1+R_f}$$

$$V_0 = \frac{R_f [I_B^- (R_1+R_f) - I_B^+ R_f - I_B^+ R_1]}{R_1+R_f}$$

$$V_0 = \frac{R_f [I_B^- (R_1+R_f) - I_B^+ (R_f + R_1)]}{R_1+R_f}$$

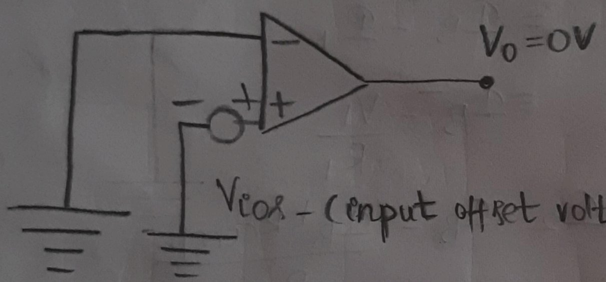
$$V_0 = R_f I_B^- - \frac{R_f I_B^+ (R_f + R_1)}{R_1+R_f}$$

$$V_0 = R_f I_B^- - R_f I_B^+$$

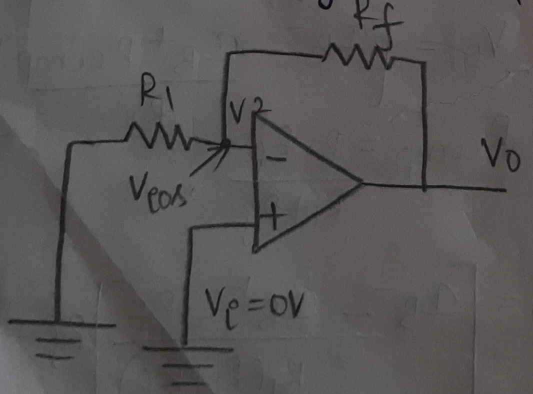
$$V_0 = R_f [I_B^- - I_B^+]$$

$$V_0 = R_f [I_{os}].$$

05/09/2023 (iii) Input offset voltage:



The voltage should be given to op-Amp in order to nullify the o/p voltage.



$$V_0 = \left[1 + \frac{R_f}{R_1}\right] V_{eos}$$

$$V_{eos} = |V_e - V_2|$$

$$V_{eos} = |0 - V_2|$$

$$V_2 = \frac{\text{Voltage across the resistor}}{\text{Total component (resistors)}} \times \text{i/p voltage}$$

$$V_2 = \left(\frac{R_1}{R_1+R_f}\right)V_0$$

$$V_0 = \left(\frac{R_1+R_f}{R_1}\right)V_2$$

$$V_{ios} = |V_i - V_2| \text{ \& } V_i = 0$$

$$V_0 = \left[1+\frac{R_f}{R_1}\right]V_{ios}$$

(iv) Thermal drift:

* Bias current, offset current and offset voltage may change with temperature.
* A circuit carefully nullified at 25°C may not remain same if temperature varies.
* The change due to temperature is referred as thermal drift.

$$\text{Thermal drift in i/p offset current} = \frac{\Delta I_{os}}{\Delta T}$$

$$\text{Thermal drift in i/p bias current} = \frac{\Delta I_B}{\Delta T}$$

$$\text{Thermal drift in i/p offset voltage} = \frac{\Delta V_{ios}}{\Delta T}$$

AC characteristics of Op-Amp:

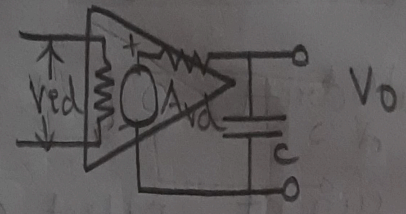
* Frequency response
* Slew rate
* Stability of Op-Amp
* Frequency compensation of op-Amp.

(i) Frequency response:

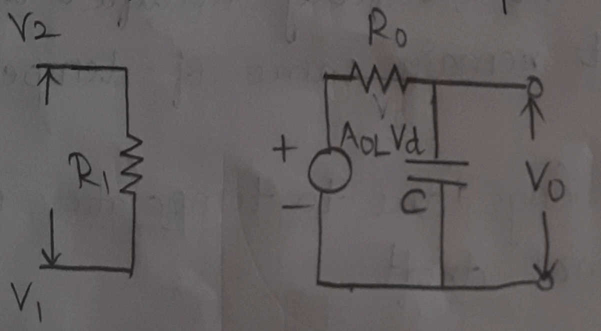
* The variation in operating frequency will cause variations in gain and phase angle.

* The manner in which the gain of the Op-Amp respond to different frequencies is called frequency response.

09/2023



* Frequency response should be uniform. It varies due to the capacitance effect.



Open loop gain (A_{OL}) = 90 dB.

* If frequency ↑ gain will be ↓ ⇒ this condition is known as role off.

⇓

Gain = 20 dB.

* As per voltage divider rule,

$$= \frac{\text{Voltage across the component}}{\text{Total components}} \times \text{Input voltage.}$$

Voltage across 'c', [Capacitor is defined by '$-jxc$']

$$V_0 = \frac{-jxc}{R_0 - jxc} \times A_{OL} V_d$$

$$\frac{V_0}{V_d} = \frac{\frac{1}{Jxc}}{R_0 - jxc} \times A_d \quad \left[j = -\frac{1}{j} \right]$$

$$\frac{V_0}{V_d} = \frac{\frac{1}{jxc}}{R_0 + \frac{1}{jxc}} \times A_d$$

$$\boxed{\frac{V_0}{V_d} = A} \rightarrow \text{gain}$$

[∵ V_d = Difference b/w i/p voltage]

$$A = \frac{\frac{1}{jxc}}{\frac{[jR_0 xc + 1]}{jxc}} \times A_{OL}$$

$$A = \frac{A_{OL}}{1 + jR_0 xc}$$

$$A = \frac{A_{OL}}{1 + jR_0 \omega_c}$$

$$\left[\omega = 2\pi f_c, \quad 2\pi R_0 = \frac{1}{f_1}, \quad x_c = \omega_c = \frac{1}{f} \right]$$

$$A = \frac{A_{OL}}{1 + jR_0 (2\pi f c)}$$

$$A = \frac{A_{OL}}{1 + jfc\left(\frac{1}{f_1}\right)}$$

f_1 = Corner frequency

$$\boxed{A = \frac{A_{OL}}{1 + j(f/f_1)}}$$

Magnitude & phase angle,

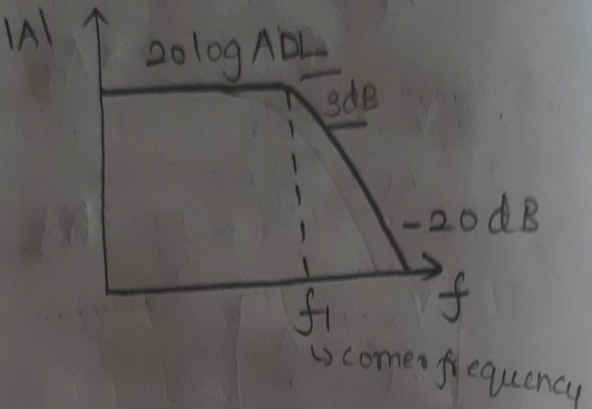
$$|A| = \frac{A_{OL}}{\sqrt{1 + (f/f_1)^2}} \quad \left[a + ib = \sqrt{a^2 + b^2} \right]$$

$$\phi = -\tan^{-1}(f/f_1) = \tan^{-1}(b/a) \quad \left[\begin{matrix} a = 1 \\ b = f/f_1 \end{matrix} \right]$$

* Op-Amp with three different corner frequencies

$$A = \frac{A_{OL} \times f_1 f_2 f_3}{[1+j(f/f_1)][1+j(f/f_2)][1+j(f/f_3)]}$$

Output waveform:

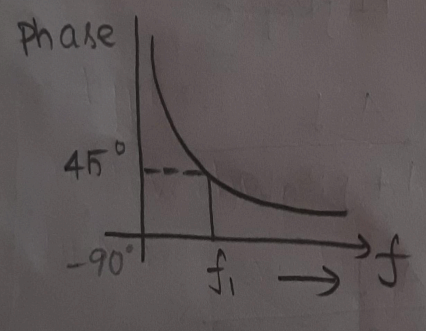


* $f<f_1 \Rightarrow$ Magnitude of gain $20 \log A_{OL}$

* $f=f_1 \Rightarrow$ 3dB down from A_{OL}

* $f>f_1 \Rightarrow$ Gain Role offe at -20 dB.

Phase characteristics:



2023 (ii) Slew rate:

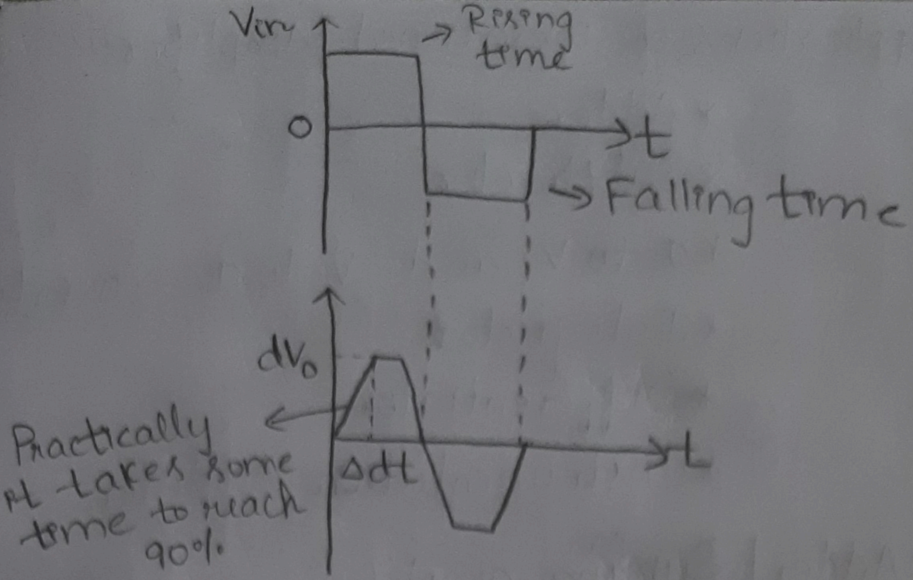
* Rate of change of an output voltage w.r.t time.

(or)

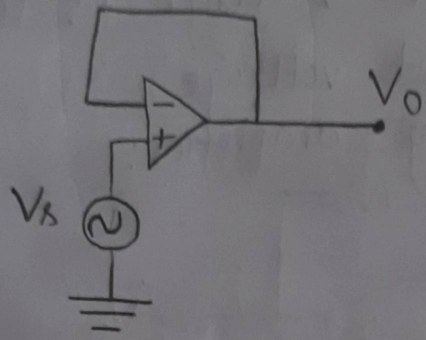
* Time the o/p takes to change from 10% to 90%.

$$SR = \frac{dv_0}{dt}\Big|_{max} \quad (or) \quad S_R = \frac{I_{max}}{C}$$

* Unit ⇒ Volts / μsec.



Consider voltage follower → output follows the input voltage so, $V_s = V_o$



$$V_s = V_o$$

(source voltage) (output voltage)

$$V_s = V_{in} \sin \omega t$$

$$V_o = V_{in} \sin \omega t$$

$$\frac{dV_o}{dt} = V_{in} \frac{d}{dt} \sin \omega t$$

$$\frac{dV_o}{dt} = \omega V_{in} \cos \omega t$$

At max $\cos \omega t = 1$

$$SR = \omega V_m \qquad [\because \omega = 2\pi f]$$

$$SR = 2\pi f V_m \quad V/sec$$

$$SR = 2\pi f_{max} V_m \times \frac{1}{10^6} \quad V/\mu sec$$

$$f_{max} = \frac{SR \times 10^6}{2\pi V_m}$$

[Full power band width]

$$= \frac{SR \times 10^6}{6.28 V_m}$$