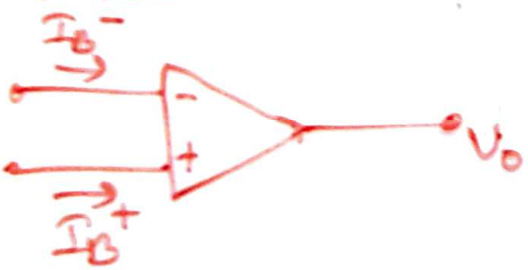
Op-Amp Characteristics

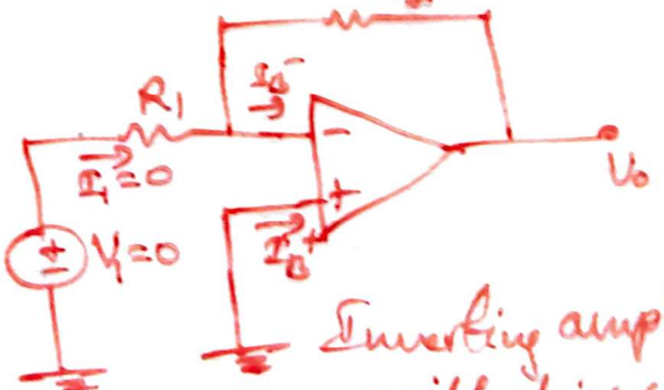
DC Characteristics

→ The non-ideal dc characteristics that add error components to the dc o/p voltage are:

i) Input bias current
ii) Input offset current
iii) Input offset voltage
iv) Thermal drift

i) Input Bias Current





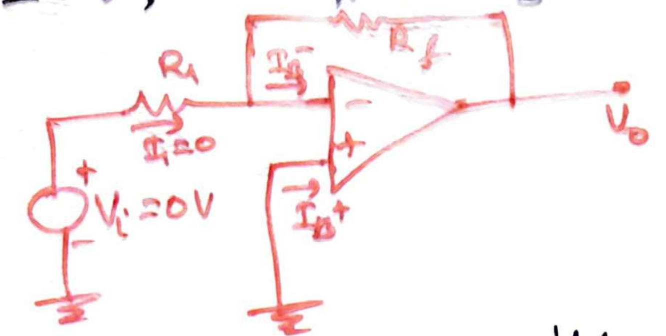
Inverting amplifier with bias currents

→ In ideal op-amp, no current is drawn from the i/p terminals.

→ Practically, i/p terminals conduct a small value of dc current to bias the i/p transistors

→ Manufacturers specify i/p bias current I_B as the average value of base currents entering into the terminals of an op-amp. So $I_B = \frac{I_B^+ + I_B^-}{2}$

→ Consider an inverting amplifier with i/p voltage $V_i = 0V$, the o/p voltage V_o should be zero volt

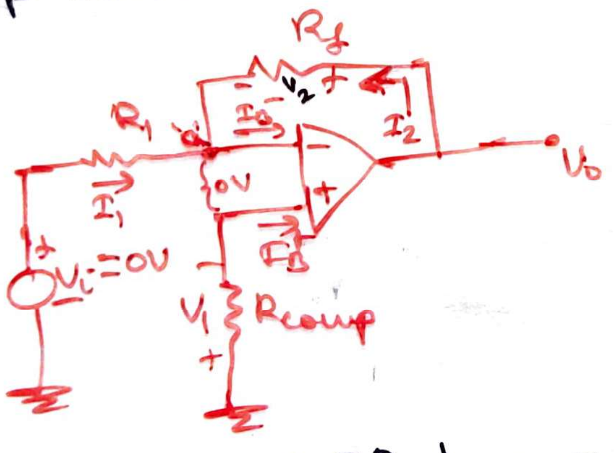


→ But we find the o/p voltage is offset by $V_o = (I_B^-) R_f$

→ For a 741 op-amp, with $1M\Omega$ feedback resistor, $V_o = 500\,nA \times 1M\Omega = 500\,mV$

→ o/p is driven to 500 mV with zero i/p because of bias currents

→ This effect can be compensated by adding a compensation resistor R_{comp} b/w non-inverting i/p terminal & ground.



$V_1 = I_B^+ R_{comp}$

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

→ With $V_i = 0$

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

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

$V_1 + 0 - V_2 + V_o = 0$

$\Rightarrow V_o = V_2 - V_1$

→ for compensation V_o should be zero for $V_i = 0$

$\therefore V_2 = V_1$

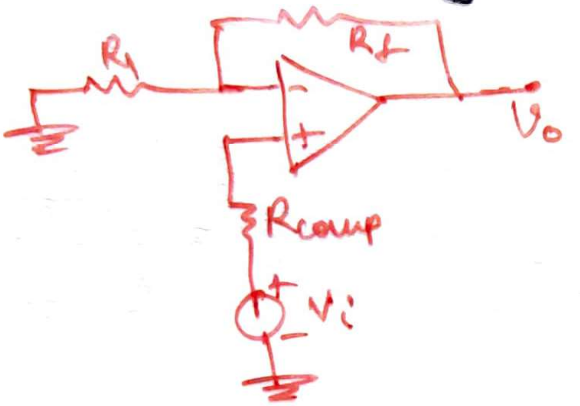
$\Rightarrow I_2 = \frac{V_1}{R_f}$

→ At node 'a' $I_B^- = I_2 + I_1 = \frac{V_1}{R_f} + \frac{V_1}{R_1} = V_1 \frac{(R_f + R_1)}{R_f R_1}$

→ Assuming $I_B^- = I_B^+$

$$\frac{V_1 (R_1 + R_f)}{R_1 R_f} = \frac{V_1}{R_{comp}} \Rightarrow R_{comp} = \frac{R_1 R_f}{R_1 + R_f} = R_1 \parallel R_f$$

→ The effect of i/p bias current in a non-inverting amplifier can also be compensated by placing a compensating resistor, R_{comp} in series with the i/p signal V_i



→ The value of R_{comp} is again equal to $R_{comp} = R_f \| R_1$

Input Offset Current

→ Bias current compensation will work if both bias currents I_B^+ & I_B^- are equal.

→ Always there will be some small difference b/w I_B^+ & I_B^-. This difference is called offset current I_{os}

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

→ Absolute value indicates that there is no way to predict which of the bias currents will be larger.

→ I_{os} for BJT op-amp is 200nA

→ I_{os} for FET op-amp is 10pA

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

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

→ At node 'a' $I_2 = I_B^- - I_1 = I_B^- - \left(\frac{I_B^+ R_{comp}}{R_1}\right)$

$$V_o = I_2 R_f - V_1 = I_2 R_f - I_B^+ R_{comp}$$

$$= \left(I_B^- - I_B^+ \frac{R_{comp}}{R_1}\right) R_f - I_B^+ R_{comp}$$

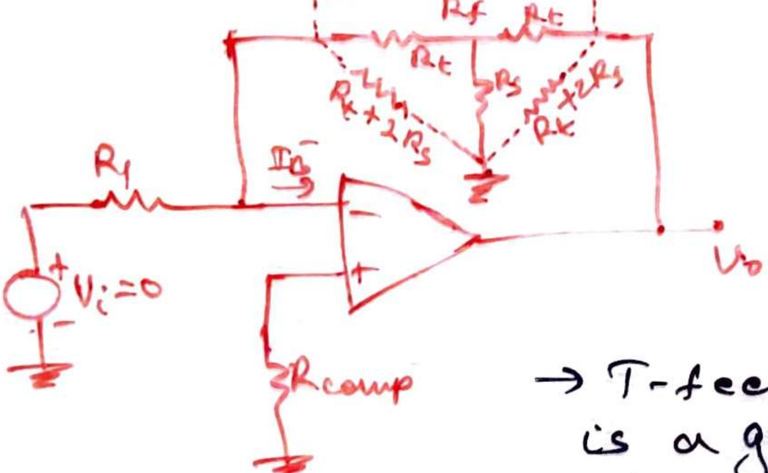
$$\Rightarrow V_o = R_f \left[I_B^- - I_B^+\right] \Rightarrow V_o = R_f I_{os}$$

→ Even with bias current compensation & with feedback resistor of 1MΩ, a 741 BJT op-amp has an o/p offset voltage $V_o = 1M\Omega \times 200nA = 200mV$ with a zero i/p voltage.

→ This effect of offset current can be minimized by keeping feedback resistance small.

→ To obtain high i/p impedance, R_1 must be kept large.

→ With R_1 large, the feedback resistor R_f must also be high so as to obtain resonable gain.



→ T-feedback n/w is a good solution which allows large feedback resistance, while keeping the resistance to ground low

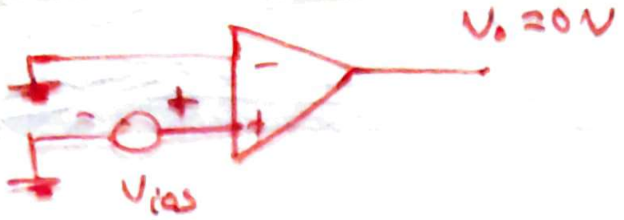
→ By T to π conversion, $R_f = \dfrac{R_t^2 + 2R_tR_s}{R_s}$

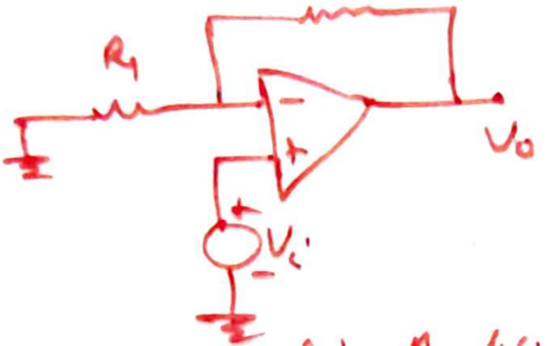
→ To design a T n/w first pick $R_t << \dfrac{R_f}{2}$, then calculate $R_s = \dfrac{R_t^2}{R_f - 2R_t}$

Input Offset Voltage

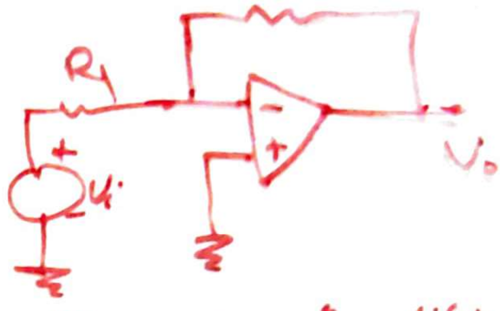
→ Due to unavoidable imbalances inside the op-amp & one have to apply a small voltage at the i/p terminals to make o/p voltage zero for zero i/p voltage.

→ This voltage is called i/p offset voltage V_{ios}.

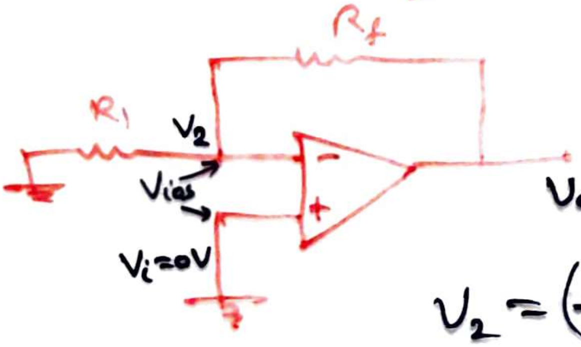




Non-inverting Amplifier



Inverting Amplifier



$$V_o = \left(1 + \frac{R_f}{R_1}\right) V_{ios}$$

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

$$V_o = \left(\frac{R_1 + R_f}{R_1}\right) V_2 = \left(1 + \frac{R_f}{R_1}\right) V_2$$

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

$$V_{ios} = V_2$$

$$\therefore \; V_o = \left(1 + \frac{R_f}{R_1}\right) V_{ios}$$

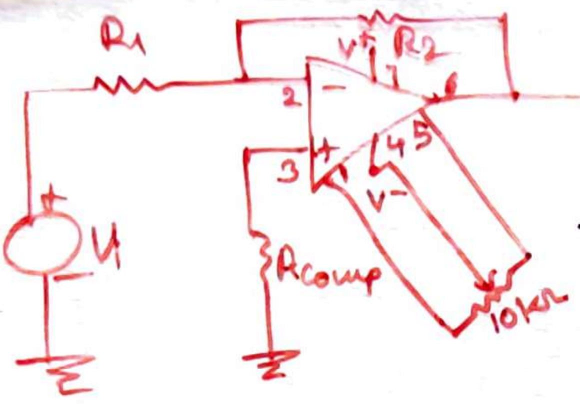
Total Output Offset Voltage

$$V_{OT} = \left(1 + \frac{R_f}{R_1}\right) V_{ios} + R_f I_B$$

→ V_{OT} could be either more or less than the offset voltage produced at o/p due to i/p bias current or i/p offset voltage alone. (Since V_{ios} & I_B could be either positive or negative w.r.t ground)

→ With R_{comp} in the ckt, $V_{OT} = \left(1 + \frac{R_f}{R_1}\right) V_{ios} + R_f I_{os}$

→ Many op-amps provide offset compensation pins to nullify the offset voltage.



→ Manufacturers recommend that a 10kΩ potentiometer be placed across offset null pins 1 & 5 & wiper be connected to negative supply pin 4

→ The position of wiper is adjusted to nullify the o/p offset voltage.

Thermal Drift

→ Bias current, offset current & offset voltage change with temperature.

→ A ckt nulled at 25°c may not remain same when temp. rises to 35°c. This is called drift.

→ Offset current drift is expressed in nA/°c & offset voltage drift in mV/°c (indicates change in offset for each degree celsius change in temp.)

→ Carefully printed ckt board layout must be used to keep op-amps away from source of heat.

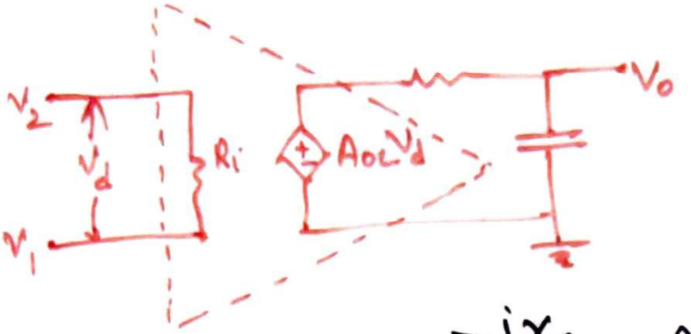
→ Forced air cooling may be used to stabilize the ambient temp.

AC Characteristics

Frequency Response

→ Ideally op-amp should have infinite bandwidth

→ But practical op-amp gain decreases (rolls-off) at higher freq's, because of a capacitive component in the equivalent ckt of op-amp.



High freq. model of an op-amp with single corner freq.

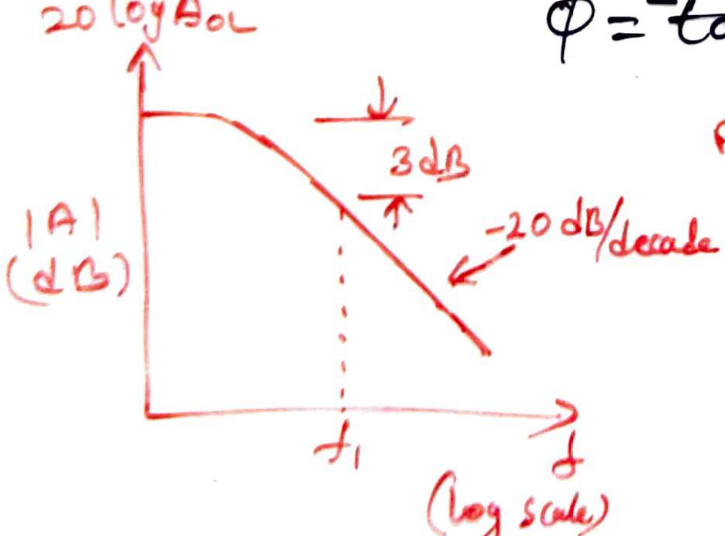
$$V_o = \frac{-jX_c}{R_o - jX_c} A_{OL} V_d$$

$$A = \frac{V_o}{V_d} = \frac{A_{OL}}{1 + j2\pi f R_o C}$$

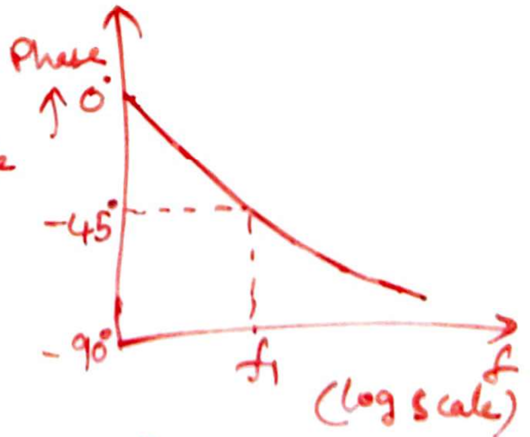
$$A = \frac{A_{OL}}{1 + j(f/f_1)} \quad \text{where } f_1 = \frac{1}{2\pi R_o C}$$

$$|A| = \frac{A_{OL}}{\sqrt{1 + (f/f_1)^2}}$$

$$\phi = -\tan^{-1}(f/f_1)$$

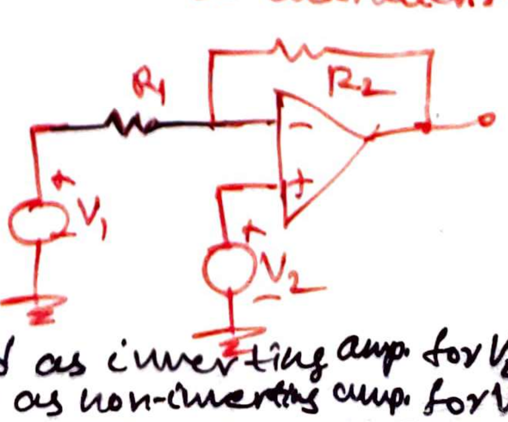


Magnitude characteristics



Phase Characteristics

Stability of an Op-amp



→ Consider an op-amp amplifier with resistor feedback n/w & maybe used as inverting amp. for $V_2 = 0$ & as non-inverting amp. for $V_1 = 0$

→ From negative feedback concepts, closed loop transfer function $A_{CL} = \frac{A}{1+A\beta}$ where

A is open loop voltage gain & β is feedback ratio

→ If characteristic equation $(1+A\beta)=0$, ckt will become unstable, leads into sustained oscillations.

$$1-(-A\beta)=0$$

$$\text{loop gain}, -A\beta = 1$$

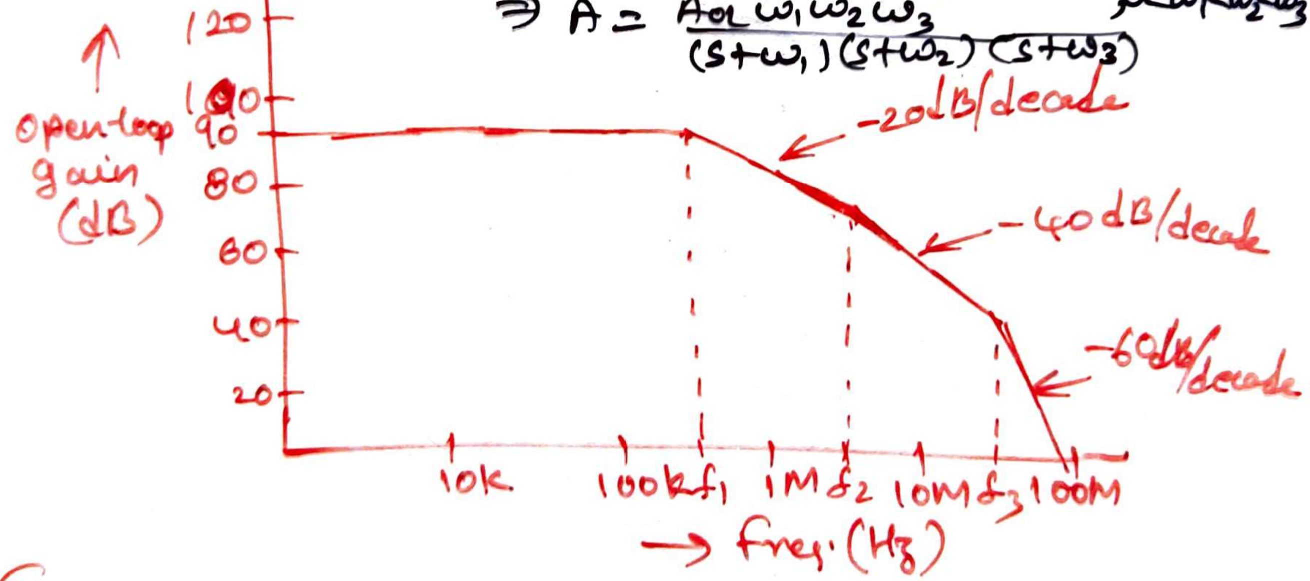
→ Since $A\beta$ is complex quantity, $|A\beta|=1$

& $\angle -A\beta = 0$ (or multiple of 2π)

$\angle A\beta = \pi$ (or odd multiple of π)

$$A = \frac{A_{OL}}{\left(1+j\frac{f}{f_1}\right)\left(1+j\frac{f}{f_2}\right)\left(1+j\frac{f}{f_3}\right)}, \quad 0<f_1<f_2<f_3$$

$$\Rightarrow A = \frac{A_{OL}\,\omega_1\omega_2\omega_3}{(s+\omega_1)(s+\omega_2)(s+\omega_3)} \quad 0<\omega_1<\omega_2<\omega_3$$



Frequency Compensation

→ In applications where one needs large bandwidth & lower closed loop gain, suitable compensation techniques are used.

→ Two types of compensation techniques

i) External Compensation

ii) Internal Compensation

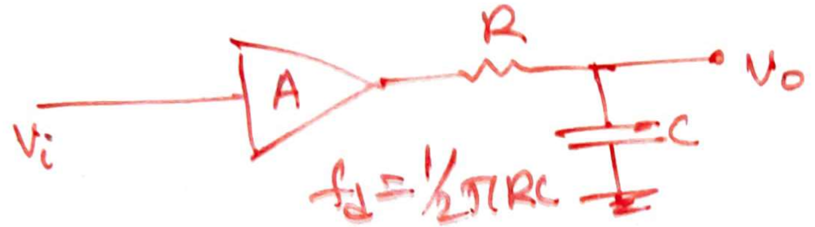
External Frequency Compensation

→ Externally connected compensating n/w alters the open-loop gain, so that roll-off rate is −20 dB/decade over a wide range of freq.

→ Dominant-pole compensation

→ Pole-zero (lag) compensation

Dominant-pole compensation



→ A is uncompensated transfer function of op-amp in open-loop condition.

→ Introducing a dominant pole by adding RC n/w in series with op-amp by connecting a capacitor C from a suitable high resistance point to ground

→ The compensated transfer function A' becomes

$$A' = \frac{V_o}{V_i}$$

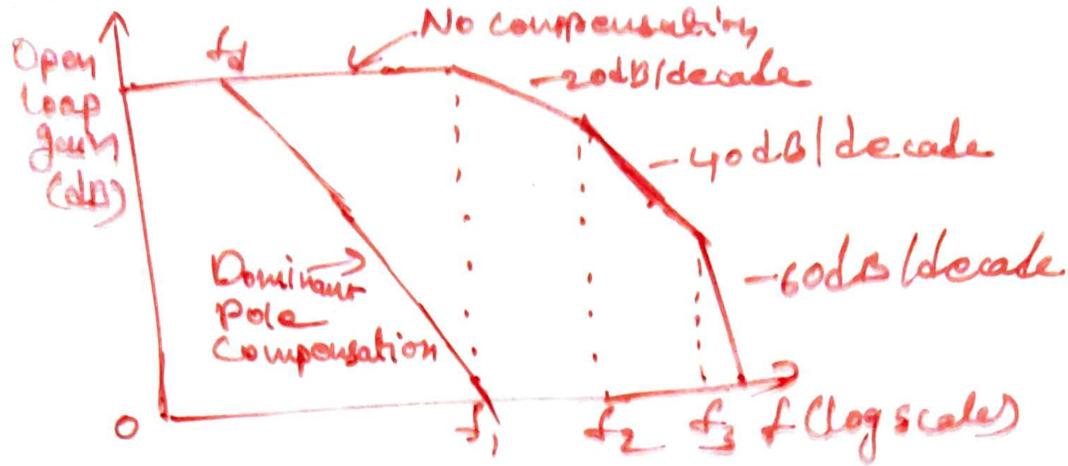
$$= A \cdot \frac{-j/\omega C}{R - j/\omega C} = \frac{A}{1 + j\frac{f}{f_d}}$$

where $f_d = \frac{1}{2\pi RC}$

$$\therefore A' = \frac{A_{OL}}{\left(1 + j\frac{f}{f_d}\right)\left(1 + j\frac{f}{f_1}\right)\left(1 + j\frac{f}{f_2}\right)\left(1 + j\frac{f}{f_3}\right)}$$

where $f_d < f_1 < f_2 < f_3$

→ The capacitance C is chosen so that the modified loop gain drops to 0dB with a slope of −20dB/decade at a freq. where poles of uncompensated T/F A contribute negligible phase shift.

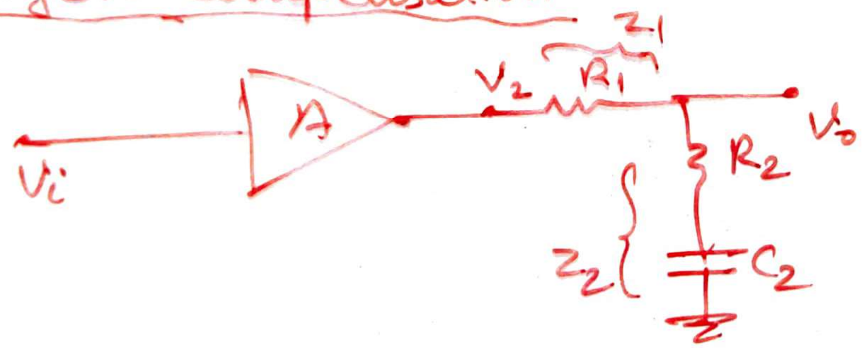


→ One disadvantage of this technique is that it reduces the open-loop bandwidth drastically

→ But noise immunity of the system is improved since the noise freq. components outside the bandwidth are eliminated.

Pole-zero Compensation

→



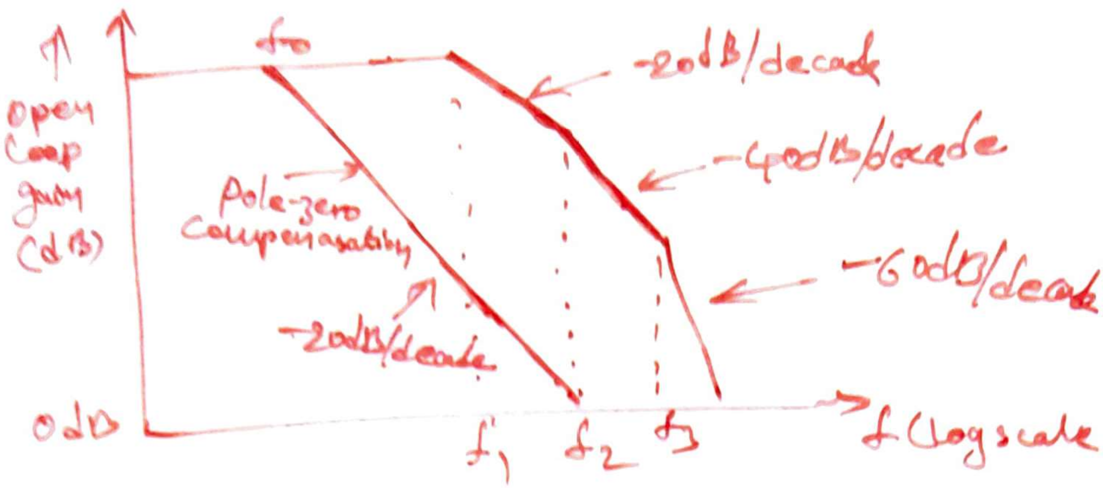
→ Uncompensated transfer function A is altered by adding both a pole & a zero

→ The zero should be at higher freq. than pole

$$\frac{V_o}{V_2} = \frac{Z_2}{Z_1+Z_2} = \frac{R_2}{R_1+R_2} \frac{1+j\frac{f}{f_1}}{1+j\frac{f}{f_0}}$$

where $Z_1 = R_1$, $Z_2 = R_2 + \frac{1}{j\omega C_2}$, $f_0 = \frac{1}{2\pi(R_1+R_2)C_2}$

$f_1 = \frac{1}{2\pi R_2 C_2}$



$$A' = \frac{V_o}{V_i} = \frac{V_o}{V_2} \cdot \frac{V_2}{V_i} = A \cdot \frac{R_2}{R_1+R_2} \cdot \frac{1+j\frac{f}{f_1}}{1+j\frac{f}{f_0}}$$

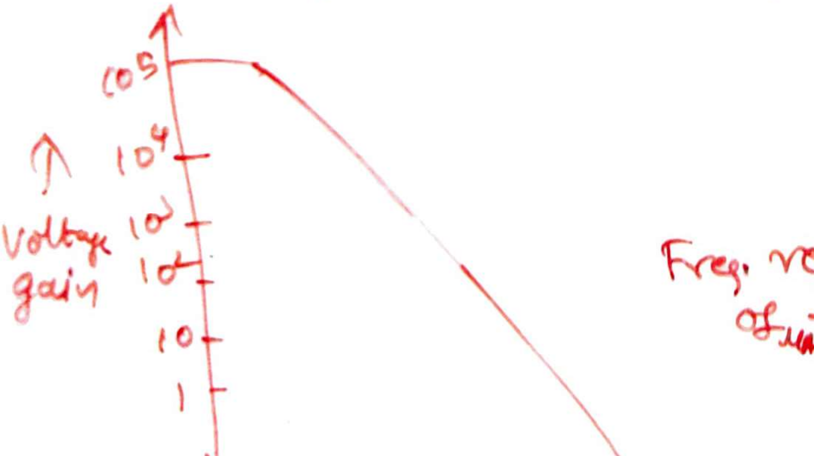
$$= \frac{A_{OL}}{\left(1+j\frac{f}{f_1}\right)\left(1+j\frac{f}{f_2}\right)\left(1+j\frac{f}{f_3}\right)} \cdot \frac{R_2}{R_1+R_2} \cdot \frac{1+j\frac{f}{f_1}}{1+j\frac{f}{f_0}}$$

$$= \frac{A_{OL}}{\left(1+j\frac{f}{f_0}\right)\left(1+j\frac{f}{f_2}\right)\left(1+j\frac{f}{f_3}\right)}$$

with $0 < f_0 < f_1 < f_2 < f_3$

& $R_2 >> R_1$ so that $\frac{R_2}{R_1+R_2} \simeq 1$

Internally Compensated Op-amp



Freq. response of μA741 opamp

→ The op-amp IC 741 contains a capacitance C_1 of 30 pF that internally shuts off signal capacitor current & thus reduces the op signal at higher freq's

Slew Rate

→ Slew rate is defined as the max. rate of change of o/p voltage caused by a step i/p voltage & is specified in V/μs.

→ A 1V/μs slew rate means that the o/p rises or falls by 1V in 1μs.

→ An ideal slew rate is infinite which means that op-amp's o/p voltage should change instantaneously in response to i/p step voltage.

→ Practical IC op-amps have slew rates from 0.1V/μs to above 1000 V/μs.

→ Slew rate improves with higher closed loop gain & dc supply voltage.

→ It is also a function to temp. & decreases with an increase in temp.

→ A capacitor within or outside an op-amp prevents the o/p voltage from responding immediately to a fast changing i/p.

→ The rate at which voltage across capacitor increases is given by,

$$\frac{dV_c}{dt} = \frac{I}{C}$$

where I is the max. current to capacitor C

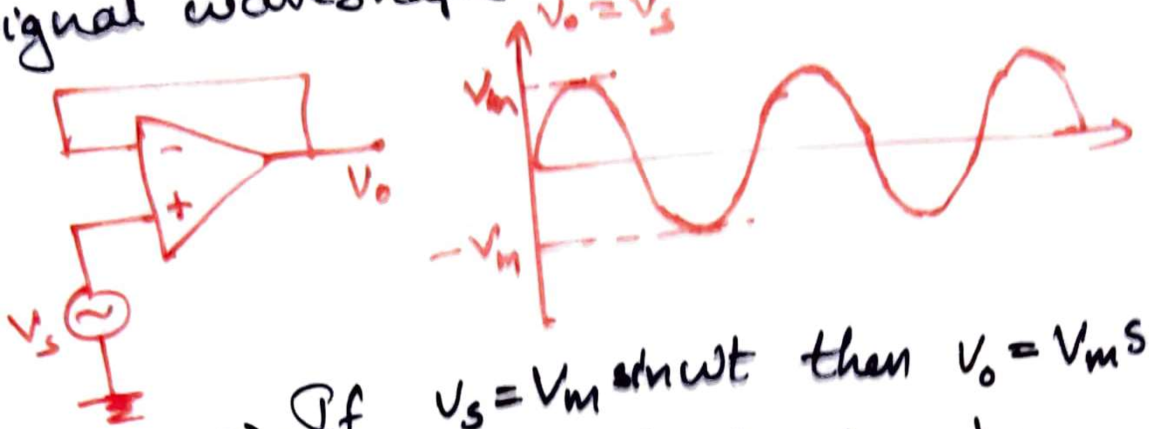
→ So for obtaining faster slew rate, op-amp should have either a higher current or a small compensating capacitor.

→ For 741C, max. internal capacitor charging current limited to about 15μA

$$SR = \left.\frac{dV_c}{dt}\right|_{max} = \frac{I_{max}}{C} = \frac{15\mu A}{30pF} = 0.5V/\mu s$$

SR → Slew Rate

→ Slew rate limits the response speed of all large signal waveshapes.



→ If $V_s = V_m \sin\omega t$ then $V_o = V_m \sin\omega t$

→ rate of change of o/p is given by

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

→ Max. rate of change of o/p occurs when $\cos\omega t = 1$

$$SR = \left.\frac{dV_o}{dt}\right|_{max} = \omega V_m$$

$$\therefore \text{Slew Rate} = 2\pi f V_m \ \ V/s$$

$$= \frac{2\pi f V_m}{10^6} \ \ V/\mu s$$

where f = i/p freq. (Hz)
V_m = peak o/p amplitude

→ If freq. or amplitude of i/p signal is increased to exceed slew rate of op-amp, the o/p will be distorted.

→ So the max. i/p freq. f_{max} at which we can obtain an undistorted o/p voltage of peak value V_m is given by

$$f_{max}(Hz) = \frac{\text{Slew Rate}}{6.28 \times V_m} \times 10^6$$

→ f_{max} is also called full power response