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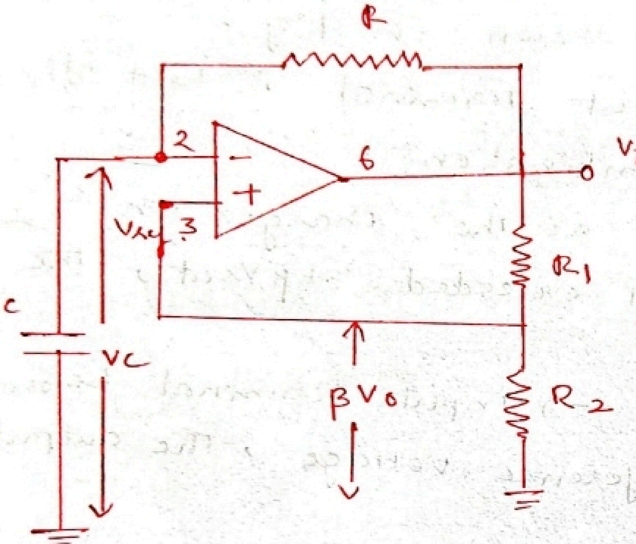
UNIT - IV - OP-AMP, IC555, IC 565 Application

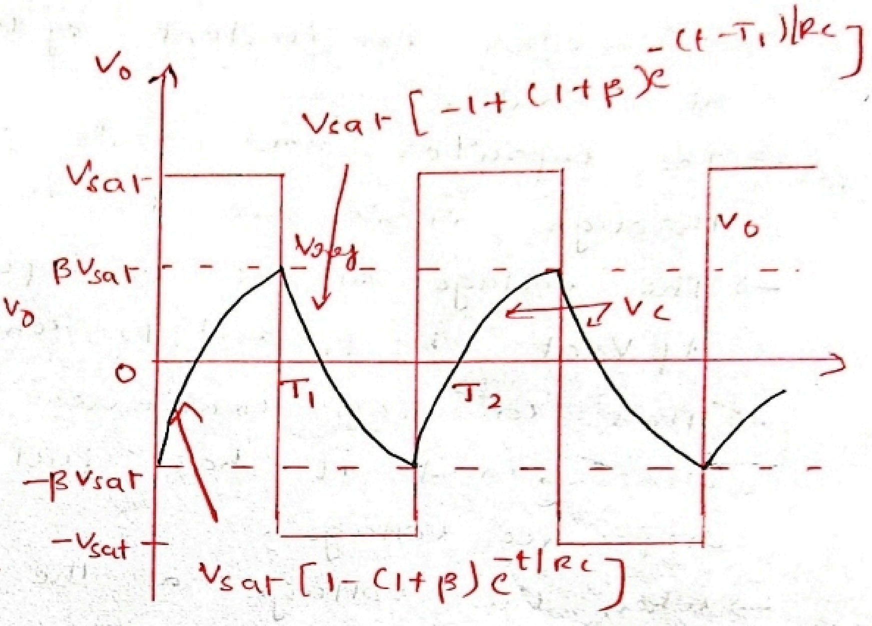
→ Wave-form generators :-

1. Squarewave generator (Astable multivibrator)

→ A simple op-amp squarewave generator is shown in fig.



(a) Simple op-amp square wave generator



(b) waveforms.

→ It is also called a free running oscillator, the principle of generation of square wave output is to force an op-amp to operate in the saturation region.

→ In the fig. fraction $\beta = \frac{R_2}{R_1+R_2}$ of the output is fed back to the (+) input terminal.

→ Thus the reference voltage V_{ref} is βV_o and may take values as $+\beta V_{sat}$ or $-\beta V_{sat}$.

→ The output is also fed back to the (−) input terminal after integrating by means of a low pass RC combination.

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→ whenever input at the (−) input terminal just exceeds V_{ref}, switching takes place resulting in a square wave output.

→ In astable multivibrator, both the states are quasi stable.

→ Consider an instant of time when the output is at $+V_{sat}$.

→ The capacitor now starts charging towards $+V_{sat}$ through resistance R, as shown in fig.

→ The voltage at the (+) input terminal is held at $+\beta V_{sat}$ by R_1 and R_2 combination.

→ This condition continues as the charge on 'c' rises, until it has just exceeded $+\beta V_{sat}$, the reference voltage.

→ when the voltage at the (−) input terminal becomes just greater than this reference voltage, the output is driven to $-V_{sat}$.

→ At this instant, the voltage on the capacitor is $+\beta V_{sat}$.

→ It begins to discharge through R, that is, charges toward $-V_{sat}$.

→ when the output voltage switches to $-V_{sat}$, the capacitor charges more and more negatively until its voltage just exceeds $-\beta V_{sat}$.

→ The output switches back to $+V_{sat}$. The cycle repeats itself as shown in fig.

→ The frequency is determined by the time it takes the capacitor to charge from $-\beta V_{sat}$ to $+\beta V_{sat}$ and vice versa.

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→ The voltage across the capacitor as a function of time is given by,

$$V_c(t) = V_f + (V_i - V_f)\, e^{-t/RC}$$

where, the final value, $V_f = +V_{sat}$

and the initial value, $V_i = -\beta V_{sat}$

$$\therefore \quad V_c(t) = V_{sat} + (-\beta V_{sat} - V_{sat})\, e^{-t/RC}$$

$$V_c(t) = V_{sat} - V_{sat}\,(1+\beta)\, e^{-t/RC}$$

At $t = T_1$, voltage across the capacitor reaches βV_{sat} and switching takes place.

$$\therefore \quad V_c(T_1) = \beta V_{sat} = V_{sat} - V_{sat}\,(1+\beta)\, e^{-T_1/RC}$$

$$\beta \cancel{V_{sat}} = \cancel{V_{sat}}\left[1 - (1+\beta)\, e^{-T_1/RC}\right)$$

$$(1+\beta)\, e^{-T_1/RC} = 1-\beta$$

$$e^{-T_1/RC} = \frac{1-\beta}{1+\beta}$$

$$e^{T_1/RC} = \frac{1+\beta}{1-\beta}$$

$$\frac{T_1}{RC} = \ln\frac{1+\beta}{1-\beta}$$

$$T_1 = RC \ln\frac{1+\beta}{1-\beta}$$

This give only one half of the period.

Total time period,

$$T = 2T_1 = 2RC \ln\frac{1+\beta}{1-\beta}$$

and the output wave form is symmetrical.

→ If $R_1 = R_2$, then $\beta = 0.5$ and $T = 2RC \ln 3$. and for $R_1 = 1.16 R_2$, it can be seen that $T = 2RC$

$$f_0 = \frac{1}{2RC}$$

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The output swings from $+V_{sat}$ to $-V_{sat}$.

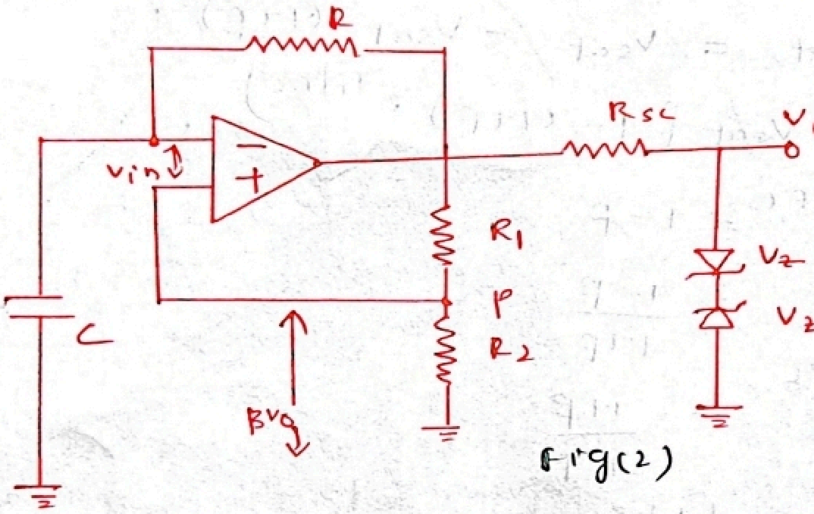
V_o peak to peak $= 2V_{sat}$.

→ The peak to peak output amplitude can be varied by varying the power supply voltage.

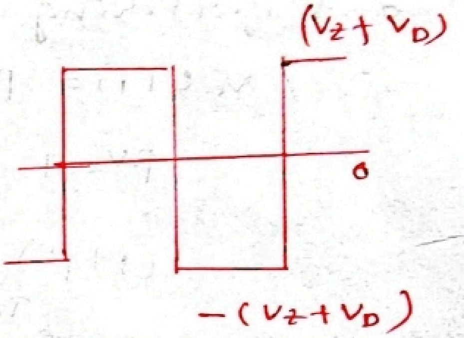
→ However, a better technique is to use back to back zener diodes as shown in fig (2)

→ The output voltage is regulated to $\pm(V_z + V_D)$ by the zener diodes.

$$V_o \text{ peak-to-peak} = 2(V_z + V_D)$$



Fig(2)



Use of back to back zener diodes.

→ If an asymmetric square wave is desired, then zener diodes with different breakdown voltages V_{z1} & V_{z2} may be used.

→ Then the output is either V_{o1} or V_{o2}, where $V_{o1} = V_{z1} + V_D$ and $V_{o2} = V_{z2} + V_D$.

→ An alternative method to get asymmetric square wave output is to add a dc voltage source V in series R_2 as shown in fig(3)

→ Now the capacitor C swings between the voltage levels $(\beta V_{sat} + V)$ and $(-\beta V_{sat} + V)$.

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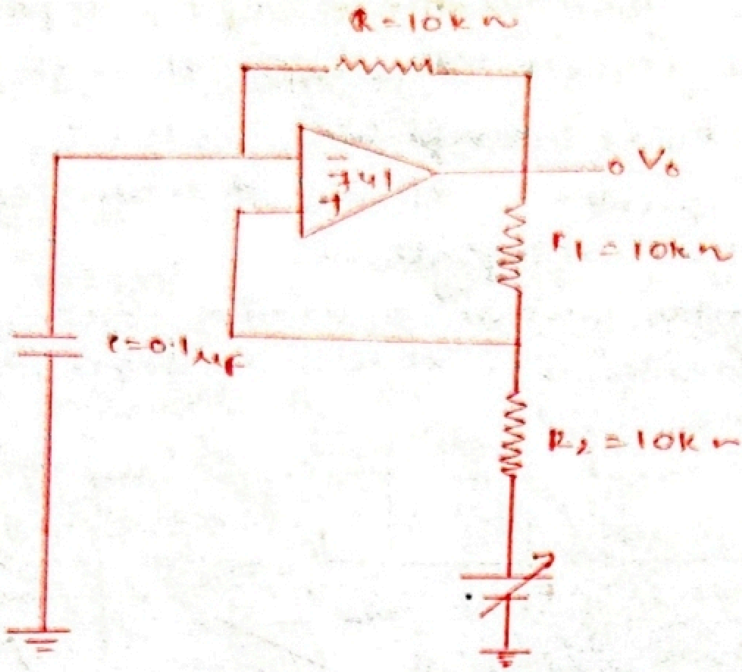


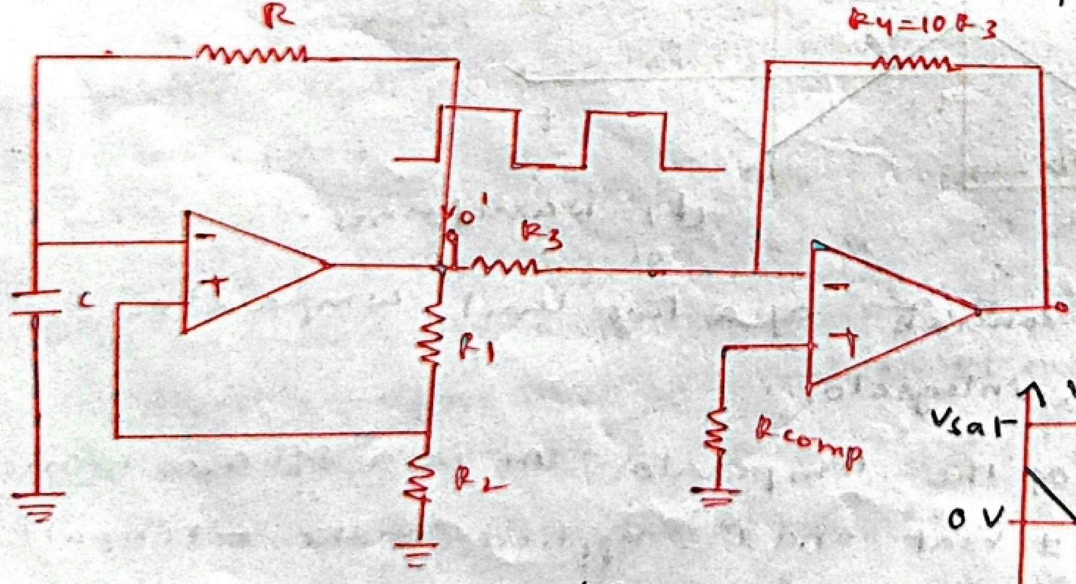
Fig (3) Asymmetric square wave generator.

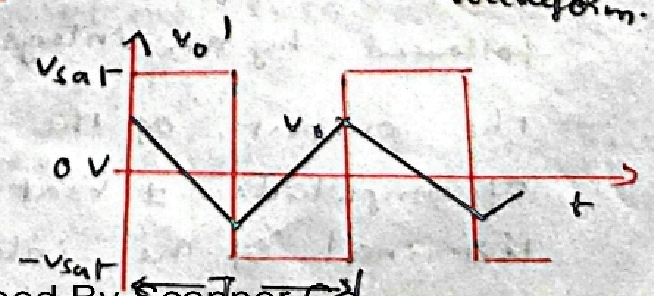
→ Triangular wave generator :-

→ A triangular wave can be simply obtained by integrating a square wave as shown in fig. (a).

→ The frequency of the square wave & triangular wave is the same.

→ The amplitude of the square wave is constant at $\pm V_{sat}$, the amplitude of triangular wave will decrease as the frequency increases.





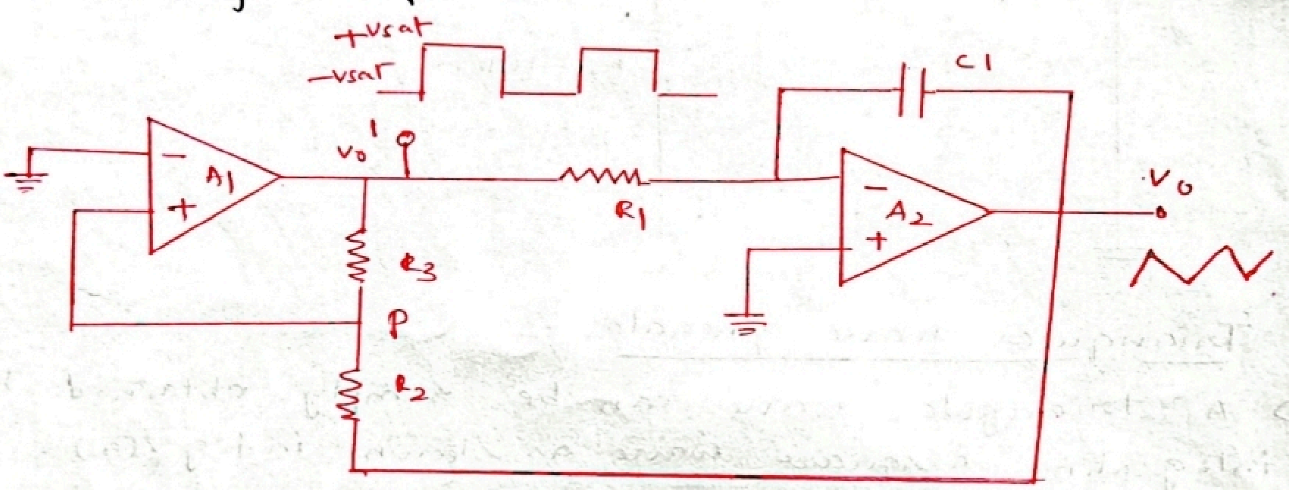
(b) output waveform.

Fig (a) Triangular waveform generator

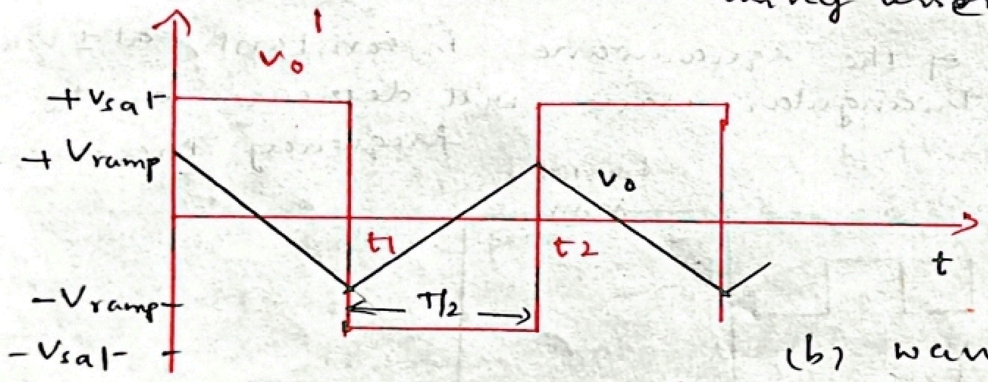
→ This is because the reactance of the capacitor C_2 in the feedback circuit decreases at high frequencies.

→ A resistance R_4 is connected across C_2 to avoid the saturation problem at low frequencies as in the case of practical integrator.

→ Another triangular wave generator using lesser number of components is shown in fig(2).



Fig(2) Triangular waveform generator
(a) using lesser components.



(b) waveforms.

→ It basically consists of a two level comparator followed by an integrator.

→ The output of the comparator A1 is a square wave of amplitude ± Vsat and is applied to the (-) input terminal of the integrator A2 producing a triangular wave.

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→ This triangular wave is fed back as input to the comparator A_1 through a voltage divider $R_2 R_3$

→ Initially, let us consider that the output of comparator A_1 is at $+V_{sat}$.

→ The output of the integrator A_2 will be a negative going ramp as shown in fig (b).

→ Thus one end of the voltage divider $R_2 R_3$ is at a voltage $+V_{sat}$ and the other at the negative going ramp of A_2.

→ At a time $t = t_1$, when the negative going ramp attains a value of $-V_{ramp}$, the effective voltage at point 'p' becomes slightly less than 0V.

→ This switches the output of A_1 from positive saturation to negative saturation level $-V_{sat}$.

→ During the time when the output of A_1 is at $-V_{sat}$, the output of A_2 increases in the positive direction.

→ And at the instant $t = t_2$, the voltage at point 'p' becomes just above 0V, there by switching the output of A_1 from $-V_{sat}$ to $+V_{sat}$.

→ The cycle repeats and generates a triangular waveform.

→ It can be seen that the frequency of the square wave and triangular wave will be the same.

→ However, the amplitude of the triangular wave depends upon the RC value of the integrator A_2 and the output voltage level of A_1.

→ The output voltage of A_1 can be set to desired level by using appropriate zener diodes.

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→ The frequency of the triangular waveform can be calculated as follows :

→ The effective voltage at point P during the time when output of A_1 is at $+V_{sat}$ level is given by ,

$$V_P = -V_{ramp} + \frac{R_2}{R_2+R_3}\left[+V_{sat} - (-V_{ramp})\right]$$

→ at $t = t_1$, the voltage at point P becomes equal to zero .

$$\therefore \quad 0 = -V_{ramp} + \frac{R_2}{R_2+R_3}\left[+V_{sat} - (-V_{ramp})\right]$$

$$0 = -V_{ramp} + \frac{R_2}{R_2+R_3} V_{sat} - \left((-V_{ramp})\frac{R_2}{R_2+R_3}\right)$$

$$0 = -V_{ramp}\left[1 - \frac{R_2}{R_2+R_3}\right] + \frac{R_2}{R_2+R_3} V_{sat}$$

$$0 = -V_{ramp}\left[\frac{R_2+R_3-R_2}{R_2+R_3}\right] + \frac{R_2}{R_2+R_3} V_{sat}$$

$$0 = -V_{ramp}\left[\frac{R_3}{R_2+R_3}\right] + \frac{R_2}{R_2+R_3} V_{sat}$$

$$-\frac{R_2}{R_2+\cancel{R_3}} V_{sat} = -V_{ramp}\left(\frac{R_3}{R_2+\cancel{R_3}}\right)$$

$$\boxed{\therefore -V_{ramp} = \frac{-R_2}{R_3}(+V_{sat})}$$

similarly $t = t_2$, when the output of A_1 switches from $-V_{sat}$ to $+V_{sat}$,

$$0 = V_{ramp} + \frac{R_2}{R_2+R_3}\left[+V_{sat} - V_{ramp}\right]$$

$$0 = V_{ramp} + \left(\frac{R_2}{R_2+R_3}\right) V_{sat} - V_{ramp}\frac{R_2}{R_2+R_3}$$

$$0 = V_{ramp}\left[1 - \frac{R_2}{R_2+R_3}\right] + \left(\frac{R_2}{R_2+R_3}\right) V_{sat}$$

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$$0 = V_{ramp}\left[\frac{R_2+R_3-R_2}{R_2+R_3}\right] + \frac{R_2}{R_2+R_3} V_{sat}$$

$$0 = V_{ramp}\left(\frac{R_3}{R_2+R_3}\right) + \frac{R_2}{R_2+R_3} V_{sat}$$

$$V_{ramp}\left(\frac{R_3}{R_2+\cancel{R_3}}\right) = -\frac{R_2}{R_2+\cancel{R_3}} V_{sat}$$

$$\boxed{V_{ramp} = -\frac{R_2}{R_3} V_{sat}}$$

∴ Peak-to-peak amplitude of the triangular wave is $V_o(p\text{-}p) = +V_{ramp} - (-V_{ramp})$

$$= \frac{R_2}{R_3} V_{sat} + \frac{R_2}{R_3} V_{sat}$$

$$\boxed{V_o(p\text{-}p) = 2 \cdot \frac{R_2}{R_3} V_{sat}}$$

→ The output switches from $-V_{ramp}$ to $+V_{ramp}$ in half the time period $T/2$.

→ Putting the values in the basic integrator equation

$$V_o = -\frac{1}{RC}\int v_i\,dt$$

$$V_o(p\text{-}p) = -\frac{1}{R_1C_1}\int_0^{T/2} (-V_{sat})\,dt$$

$$= \frac{V_{sat}}{R_1C_1}(T/2)$$

or $$T = 2R_1C_1 \frac{V_o(p\text{-}p)}{V_{sat}}$$

→ putting the value of $V_o(p\text{-}p)$, we get

$$\boxed{T = \frac{2R_1C_1}{V_{\cancel{sat}}}\left(2\frac{R_2}{R_3}V_{\cancel{sat}}\right) = 4\frac{R_1C_1R_2}{R_3}}$$

→ Hence the frequency of oscillation f_o is

$$\boxed{f_o = \frac{1}{T} = \frac{R_3}{4R_1C_1R_2}}$$

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→ <u>sawtooth wave generator</u>:

→ The difference between the triangular and sawtooth waveforms is that the rise time of the triangular wave is always equal to its fall time. i.e, the same amount of time is required for the triangular wave to swing from $-V_{ramp}$ to $+V_{ramp}$ as from $+V_{ramp}$ to $-V_{ramp}$.

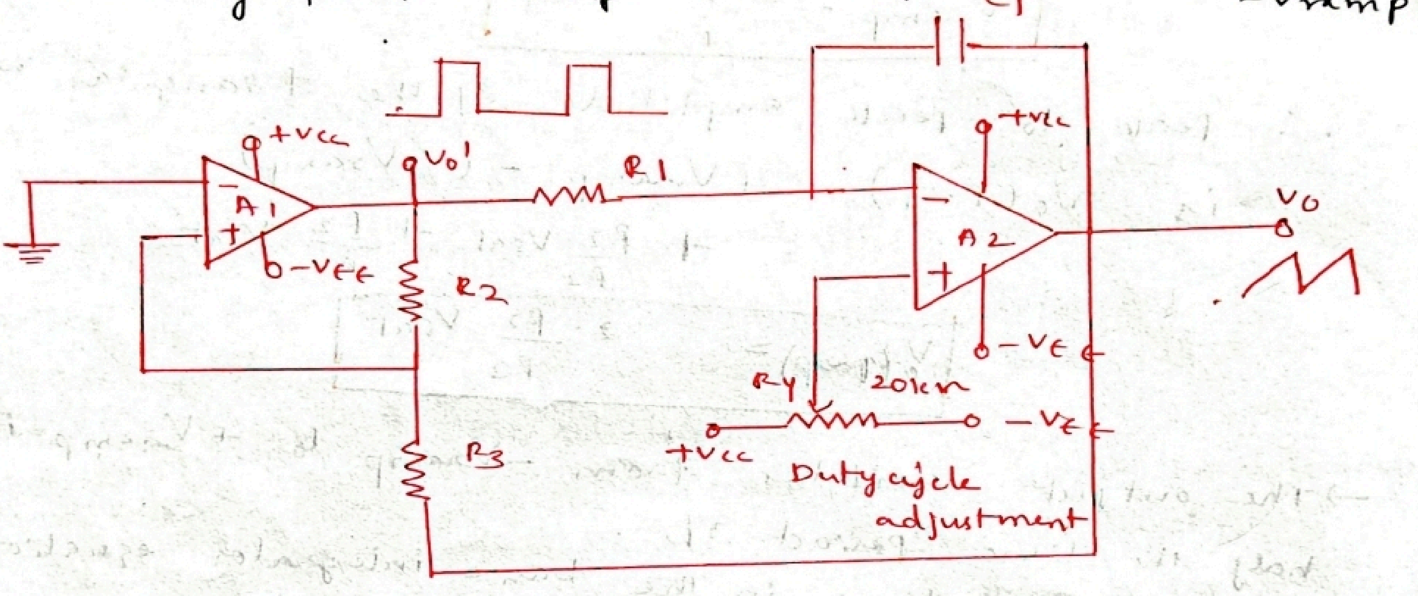
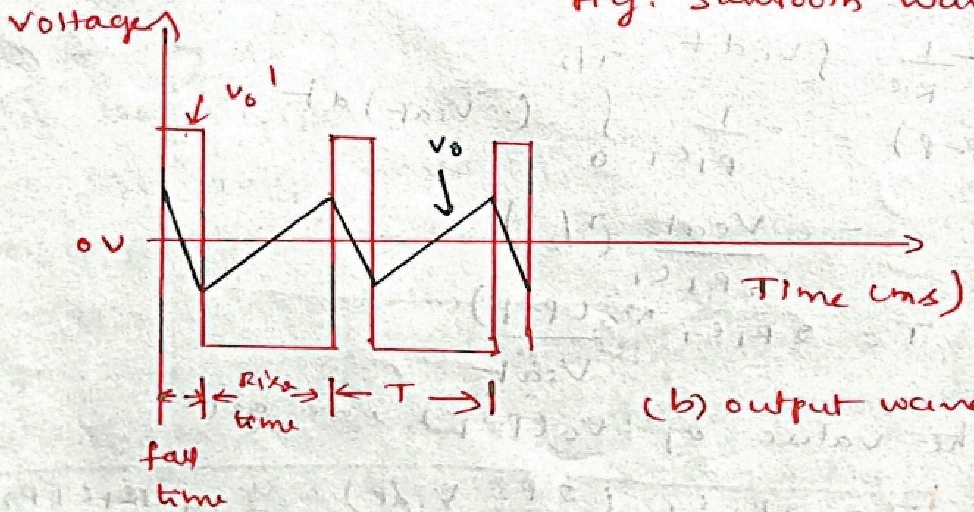


Fig. Sawtooth wave generator



(b) output waveform.

→ On the other hand, the sawtooth waveform has unequal rise and fall times. i.e, it may rise positively many times faster than it falls negatively or vice versa.

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→ The triangular wave generator can be converted into a sawtooth wave generator by injecting a variable dc voltage into the non-inverting terminal of the integrator A_2.

→ This can be accomplished by using the potentiometer and connecting it to the +Vcc and −VEE as shown.

→ Depending on the R_4 setting, a certain dc level is inserted in the output of A_2.

→ Now, suppose that the output of A_1 is a square wave and the potentiometer R_4 is adjusted for a certain dc level.

→ This means that the output of A_2 will be a triangular wave, riding on some dc level that is a function of the R_4 setting.

→ The duty cycle of the square wave will be determined by the polarity and amplitude of this dc level.

→ A duty cycle less than 50% will then cause the output of A_2 to be sawtooth.

→ With the wiper at the center of R_4, the output of A_2 is a triangular wave.

→ For any other position of R_4 wiper, the output is a sawtooth waveform.

→ Specifically as the R_4 wiper is moved toward −VEE, the rise time of the sawtooth wave becomes longer than the fall time as shown in fig..

→ On the other hand, as the wiper is moved toward +Vcc, the fall time becomes longer than the risetime.

→ Also, the frequency of the sawtooth wave decreases as R_4 is adjusted toward +Vcc ·

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→ Filters :-

→ **Introduction:-**

Electric filters are used in circuits which require the separation of signals according to their frequencies.

→ Filters are widely used in communication and signal processing and in one form or another in almost all sophisticated electronic instruments.

→ Such filters can be built from (i) passive RLC components (ii) crystals or (iii) resistors, capacitors & op-amps (active filters).

→ **RC active filters:-**

→ A frequency selective electric circuit that passes electric signals of specified band of frequencies and attenuates the signals of outside the band is called an electric filter.

→ Filters may be analog or digital.

→ The simplest way to make a filter is by using passive components (resistors, capacitors, inductors).

→ This works well for high frequencies i.e, radio frequencies.

→ However, at audio frequencies, inductors becomes problematic, as the inductors become large, heavy and expensive.

→ For low frequency application, more number of turns of wire must be used which in turn adds to the series resistance degrading inductor's performance, i.e, low Q, resulting in high power dissipation.

→ The active filters overcome the aforementioned problems of the passive filters.

→ They use op-amp as the active element, and resistors and capacitors as the passive elements.

→ Op-amp is used in non-inverting configuration, it offers high input impedance Scanned By Scanner Go impedance.

→ This will improve the load drive capacity and the load is isolated from the frequency determining network.

→ The active filters have their limitation too.

→ High frequency response is limited by the gain-bandwidth (GBW) product and slew rate of the op-amp.

→ The passive filter in high frequency range is a more economic choice for applications.

→ The most commonly used filters are :

Low pass filter (LPF)
High pass filter (HPF)
Band pass filter (BPF)
Band reject filter (BRF)
All pass filter (APF)

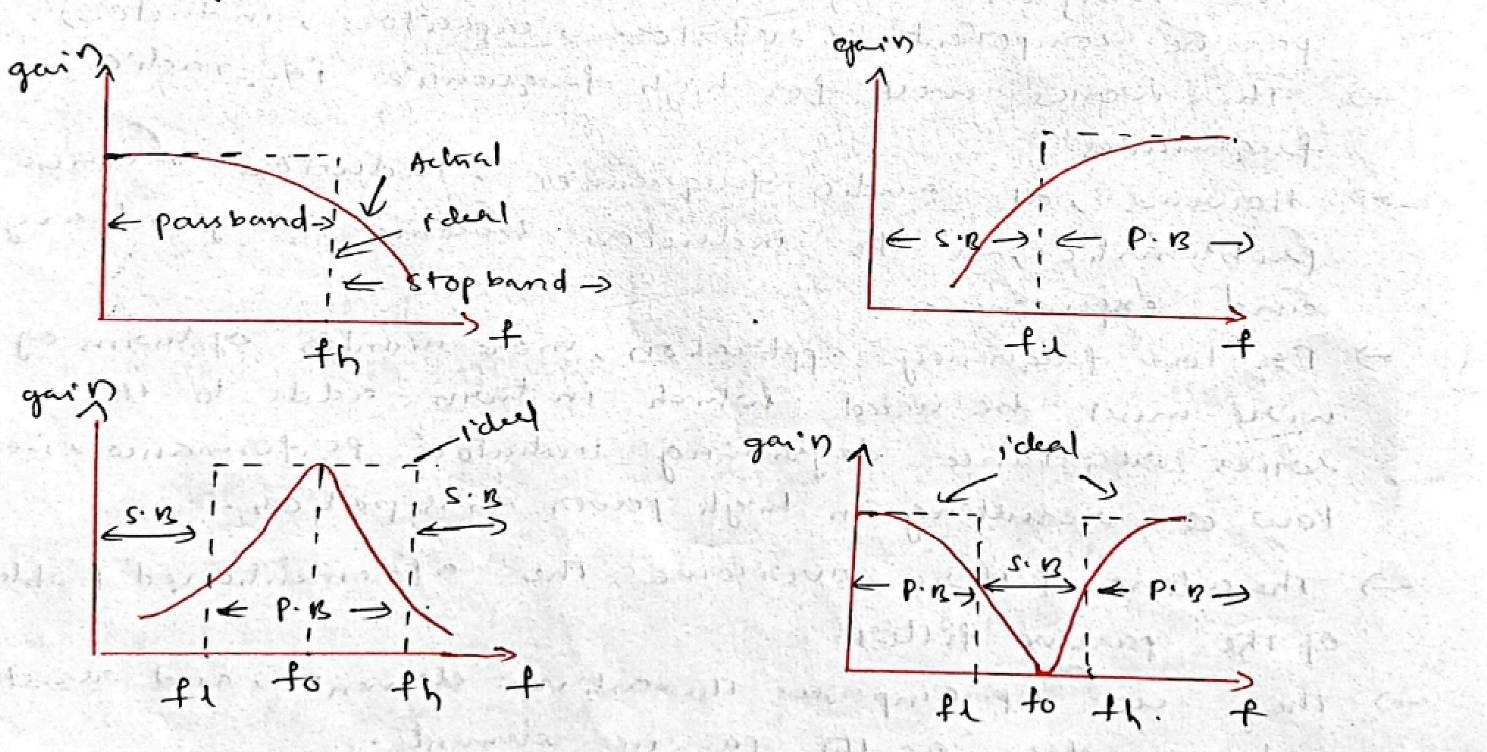

fig : frequency response of filters : LPF, HPF, BPF, BRF.

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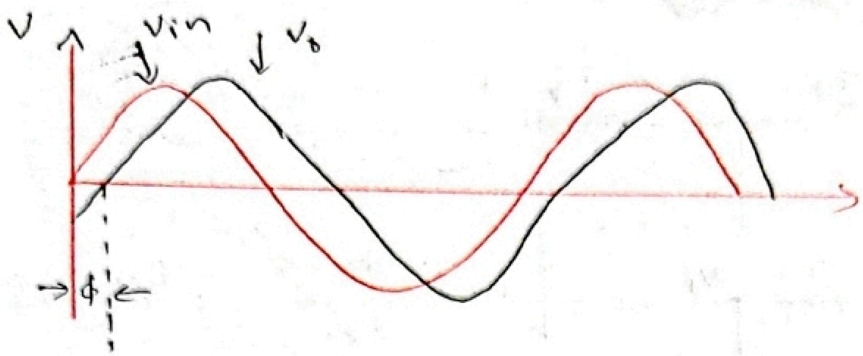

→ pass band:-
It is the range of frequencies where the signal is passed without attenuation.

→ stop band:-
It is the range of frequencies where the signal is attenuated. It is also called attenuation band.

→ f_c is centre cut of freq, $f_c = \frac{f_L + f_H}{2}$

→ Order of filter:-
The rate at which the gain of filter changes in the stop band is determined by the order of filter.

→ If the filter is first order the gain decreases at a rate of 20 dB/dec in the stop band.

→ If the filter is second order it is 40 dB/dec.

→ The commonly used filters are

(i) Butterworth filters — flat P.B & flat S.B
flat - flat filter.

(ii) chebyshev filters — ripple P.S & flat S.B

(iii) cauer filters — ripple P.S. & ripple S.B.

→ First order butterworth lowpass filter:-

R_1 & R_f determines the gain of filter.

$$V_1 = \frac{X_C}{R + X_C} V_{in} = \frac{\frac{1}{j\omega C}}{R + \frac{1}{j\omega C}} V_{in} = \frac{1}{1 + j\omega RC} V_{in}$$

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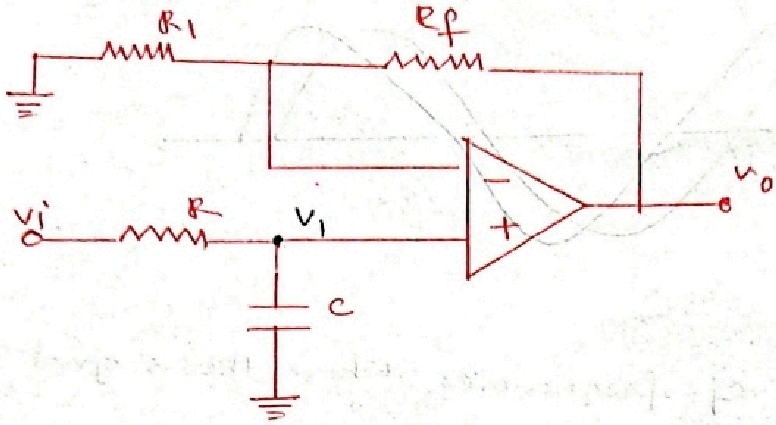
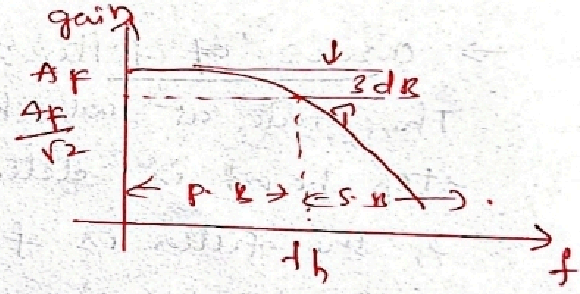


$$V_o = \left(1+\frac{R_f}{R_1}\right)V_1 = \left(1+\frac{R_f}{R_1}\right)\left(\frac{1}{1+j\omega RC}\right)V_i$$

$$\frac{V_o}{V_i} = \frac{A_F}{1+j\omega RC} = \frac{A_F}{1+j2\pi fRC}$$

Magnitude $\frac{V_o}{V_{in}} = \frac{A_F}{1+j(f/f_H)}$ where $f_h = \frac{1}{2\pi RC}$

$$\boxed{\left|\frac{V_o}{V_{in}}\right| = \frac{A_F}{\sqrt{1+(f/f_h)^2}}}$$



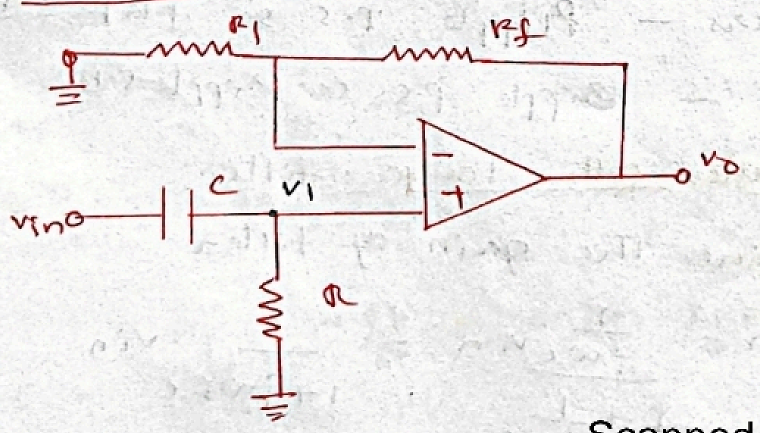
phase angle $\phi = -\tan^{-1}(f/f_h)$

for $f < f_h$, gain $= A_F$, $f=0$, max gain

$f = f_h$, gain $= 0.707A_f$

$f > f_h$, gain $< A_f$

→ First order Butterworth HPF :-



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$$V_1 = \left(\frac{R}{R+X_C}\right) V_i = \left(\frac{R}{R+\frac{1}{j\omega C}}\right) V_i = \left(\frac{j\omega RC}{1+j\omega RC}\right) V_i$$

$$V_0 = \left(1+\frac{R_f}{R_1}\right) V_1 = \left(1+\frac{R_f}{R_1}\right)\left(\frac{j\omega RC}{1+j\omega RC}\right) V_i$$

$$\frac{V_0}{V_i} = A_F\left(\frac{j\omega RC}{1+j\omega RC}\right) = A_F\left(\frac{j2\pi fRC}{1+j2\pi fRC}\right)$$

$$\frac{V_0}{V_{in}} = \frac{A_F\, j(f/f_L)}{1+j(f/f_L)} \quad \text{where } f_L = \frac{1}{2\pi RC}$$

$$\left|\frac{V_0}{V_{in}}\right| = \frac{A_F\sqrt{(f/f_L)^2}}{\sqrt{1+(f/f_L)^2}} = \frac{A_F}{\sqrt{1+(f_L/f)^2}}$$

$$\boxed{\left|\frac{V_0}{V_{in}}\right| = \frac{A_F}{\sqrt{1+(f_L/f)^2}}}$$

→ Steps to design the filter:

1. choose a value of higher cutoff freq i.e, f_h
2. select the capacitor value $C \leq 1\mu F$
3. calculate the value of R using the formula

$$R = \frac{1}{2\pi f_h C}$$

4. Finally select the values of R_1 & R_f depending upon the desired pass band gain $A_F = 1+\frac{R_f}{R_1}$

→ Design a LPF with cut off freq 1kHz and pass band gain is 2

sol:-

$$f_h = 1\text{kHz}$$

$$C = 0.01\mu F \quad \text{or } C = 0.1\mu F$$

$$R = \frac{1}{2\pi f_h C} = \frac{1}{2\pi} \times \frac{1}{10^3} \times \frac{1}{10^{-8}} = \frac{1}{2\pi} \times 10^5$$

$$= 15.9\text{k}\Omega.$$

$$A_F = 1+\frac{R_f}{R_1} = 2 \Rightarrow R_f = R_1 = 10\text{k}\Omega \text{ (say)}.$$

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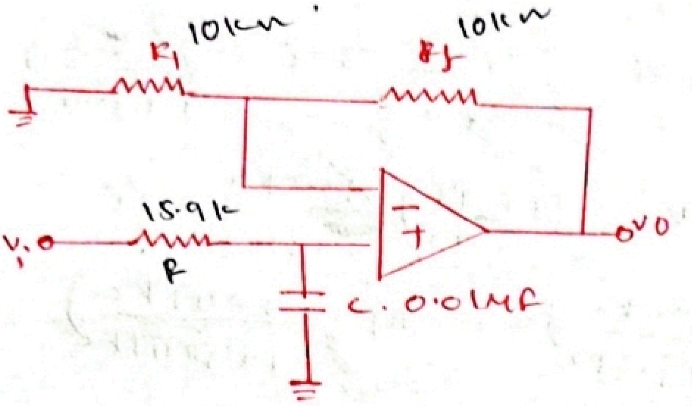


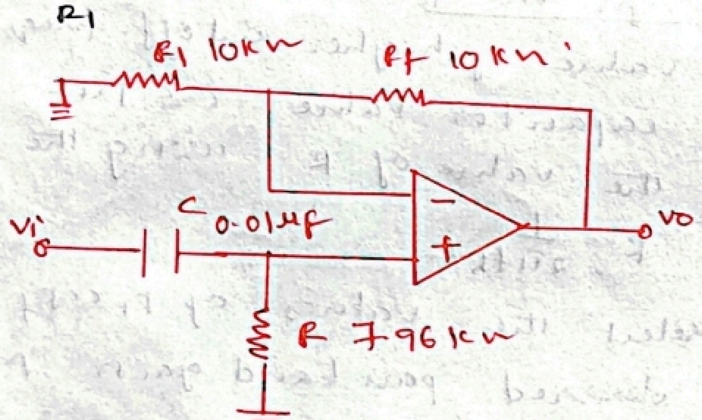
→ Design HPF at a cutoff freq of 2kHz with passband gain = 2 and draw the freq response.

sol:- $f_L = 2kHz$

$$R = \frac{1}{2\pi f_L C} = \frac{1}{2\pi \times 2\times10^2 \times 0.01\mu F}$$

$$= 7.96\,K$$

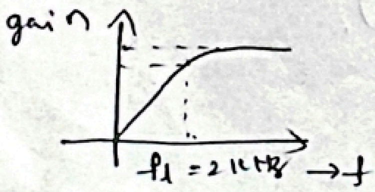
$$A_f = 1 + \frac{R_f}{R_1} = 2 \Rightarrow R_1 = R_f = 10k\Omega \text{ (say)}.$$

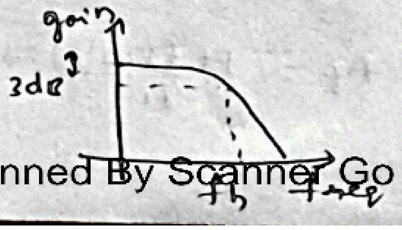


→ Response (HPF) $\frac{V_o}{V_{in}} = \frac{A_F}{\sqrt{1+(f_L/f)^2}}$ LPF, $\frac{V_o}{V_{in}} = \frac{A_F}{\sqrt{1+(f/f_H)^2}}$

freq	gain	gain(dB)
100Hz		
⋮		

freq	gain	gain(dB)
100Hz		
⋮		



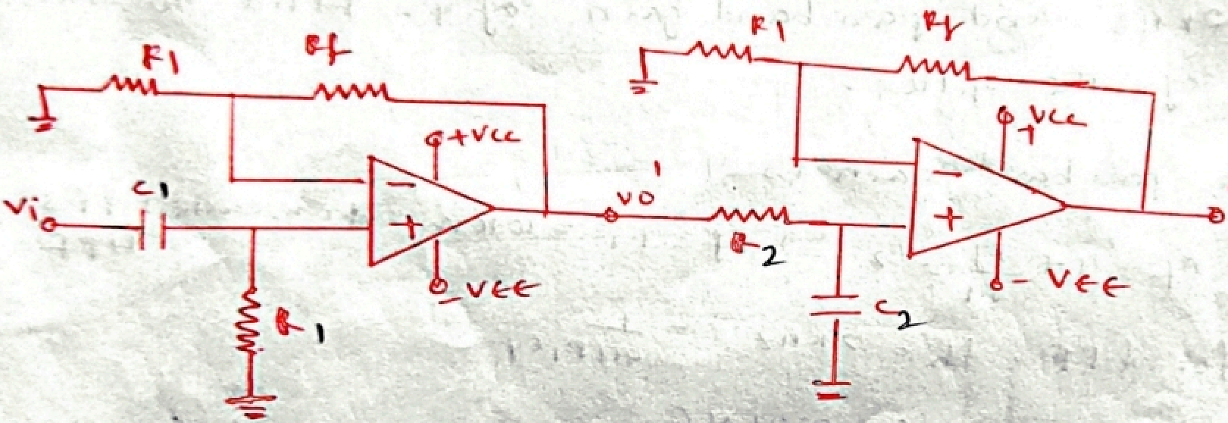


→ Band pass filter:

→ Band pass filters are classified based the quality factor 'Q', if $Q < 10$, it is called wide BPF. If $Q > 10$, it is called Narrow band pass filter. Where 'Q' is measure of selectivity & quality factor. Higher the 'Q' value, the filter is more selective.

$$f_c = \sqrt{f_h \cdot f_l}, \quad Q = \frac{f_c}{B.W} = \frac{f_c}{(f_h - f_l)}$$

→ WBPF:- It is formed by simply connecting or cascading high pass filter or low pass filter.

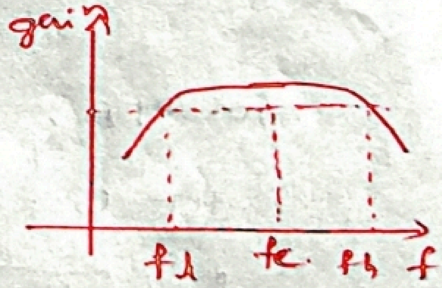


← 1st order HPF → ← 1st order LPF →

$$A_F = 1 + \frac{R_f}{R_1}$$

$$= 1 + 1 = 2$$

overall gain $= 2 \times 2 = 4$



WBPF

Magnitude of gain $= \dfrac{A_F (f/f_l)}{\sqrt{1 + (f/f_l)^2}} \times \dfrac{A_F}{\sqrt{1 + (f/f_h)^2}}$

$$= \frac{A_{FT} (f/f_l)}{\sqrt{(1 + (f/f_h)^2)(1 + (f/f_l)^2)}}$$

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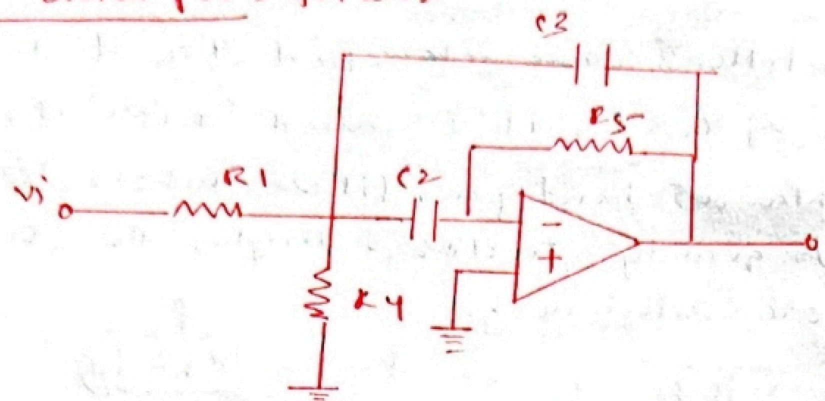
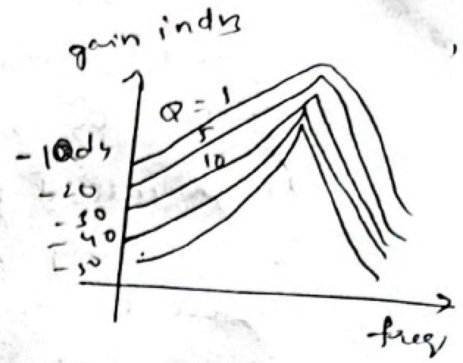
→ Narrow band pass filter:





→ higher the 'Q' sharper the filter.

→ Design a wide-band pass filter having fl = 400 KHz fh = 2KHz and pass band gain of 4. Find the value of 'Q' of the filter.

Sol:- The pass band gain is 4

$A_F = 1 + \frac{R_f}{R_1} = 2 \Rightarrow R_f = R_1 = 10k\Omega$ for each LPFs, HPF

for LPF, $f_h = 2KHZ = \frac{1}{2\pi R_1 C_1}$

$C = 0.01\mu F$

$R_1 = \frac{1}{2\pi \times 0.01\mu F \times 2K} = 7.9k\Omega.$

for HPF, $f_l = 400 Hz = \frac{1}{2\pi R_2 C_2}$

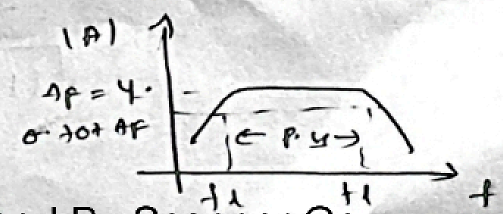
let $C_2 = 0.01\mu F$, $R_2 = 39.8k\Omega.$

$f_0 = \sqrt{f_h f_l} = \sqrt{2K \times 400} = 894.4$

$Q = \frac{f_0}{B.W} = \frac{f_0}{f_h - f_l} = \frac{894.4}{2000-400} = 0.56$ where $Q < 0$

obviously, for WBPF, Q is very low.

i/p f gain gain(db)
100
.
.
.
.



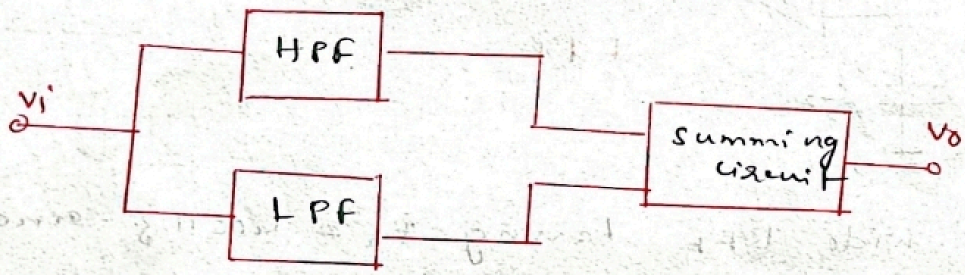
→ Band reject filters :-

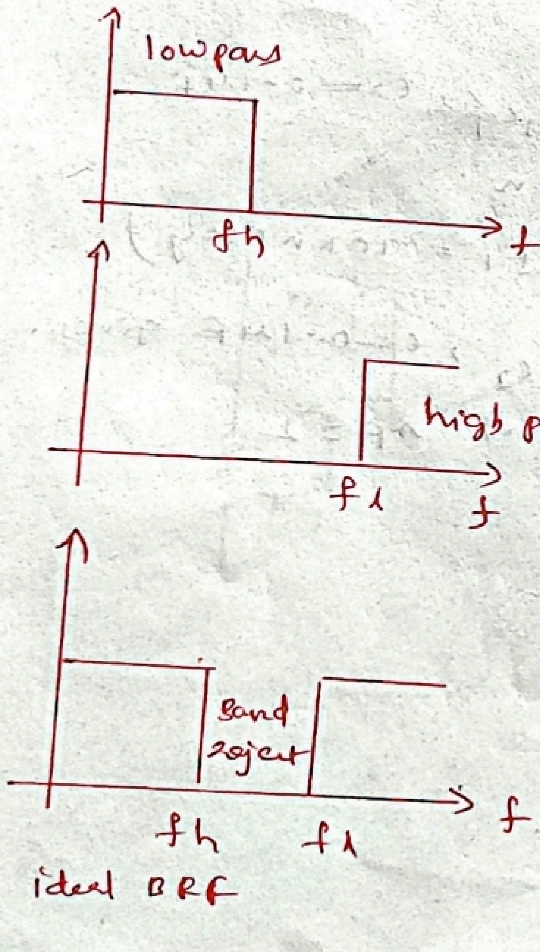
The band reject filter, often called the band-elimination or band stop filter, attenuates the frequencies in the stop band and passes them outside the band.

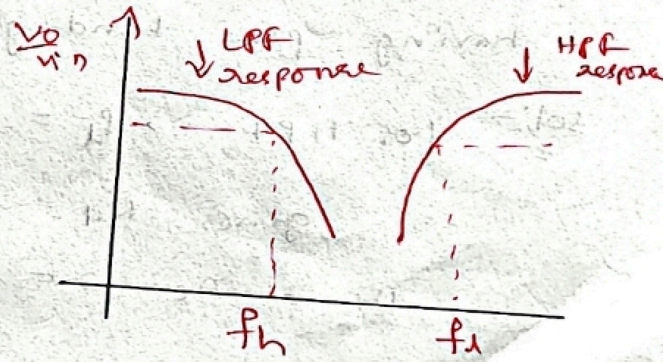
BRF → can be classified as (i) WBRFs. NBRF

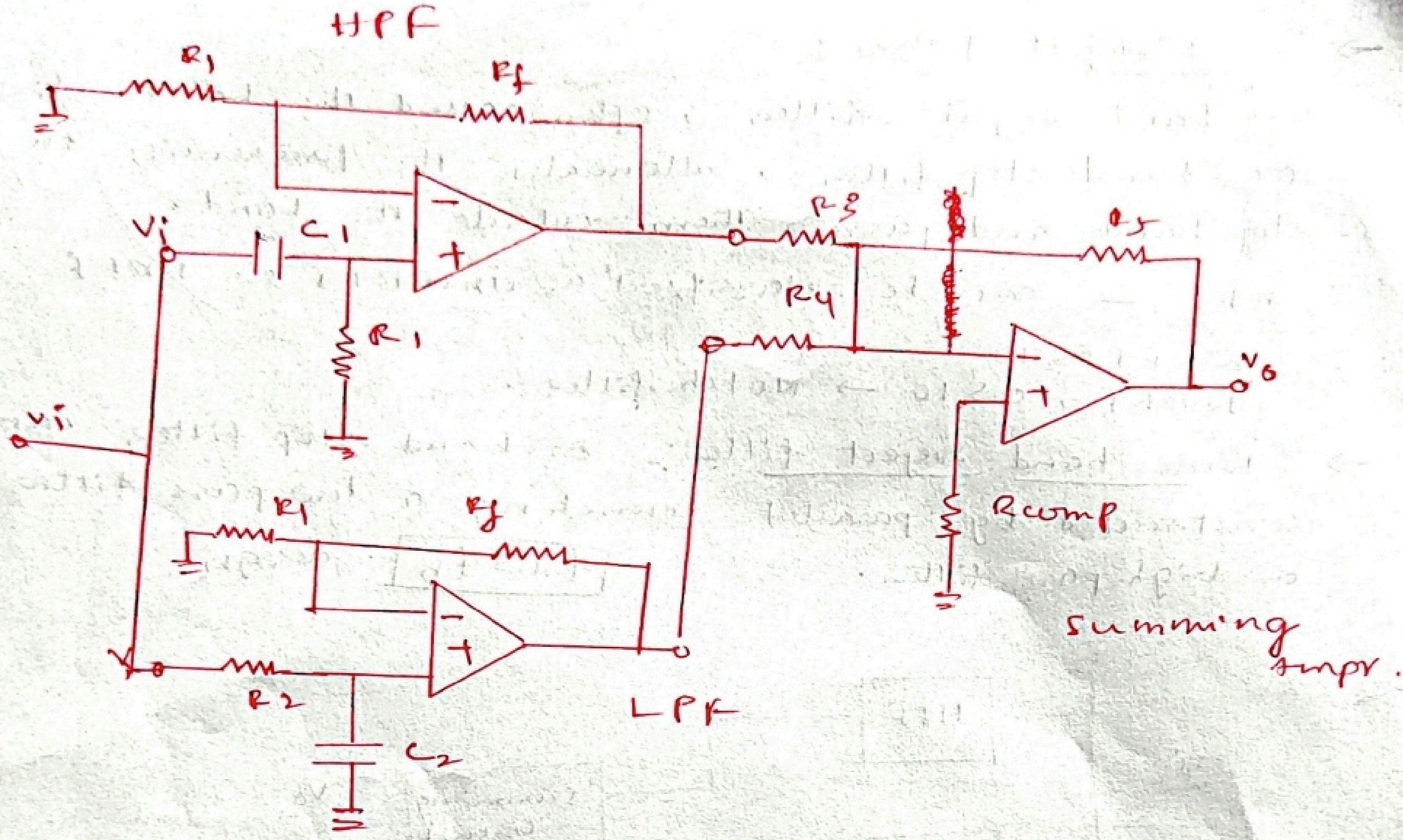
WBRF, Q< 10
NBRF, Q > 10 → Notch filter.

→ Wide band reject filter :- or band stop filter can be constructed by parallel connecting a low pass filter and a high pass filter. $\boxed{f_l > f_h}$. design.









→ Design a wide BRF having $f_h = 400\,Hz$ and $f_l = 2\,KHz$. having pass band gain as 2.

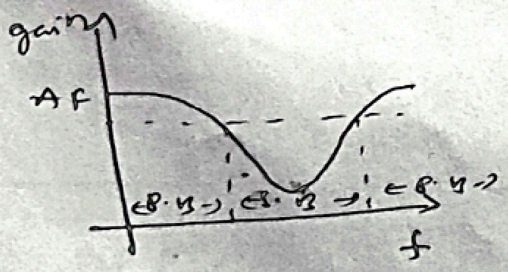
sol:- for HPF , $f_l = 2\,KHz = \frac{1}{2\pi R_1 C_1}$, $C_2 = 0.1\,\mu F$

gives $R_1 = 795\,\Omega \simeq 800\,\Omega$.

$A_F = A_0 = 2 = 1 + \frac{R_f}{R_1} \Rightarrow R_f = R_1 = 10\,K\Omega$ (say)

for LPF, $f_h = 400\,Hz = \frac{1}{2\pi R_2 C_2}$, $C = 0.1\,\mu F$ gives.

$R_1 = 39.78\,\Omega$ (choose $41\,K\Omega$) $A_F = 2$



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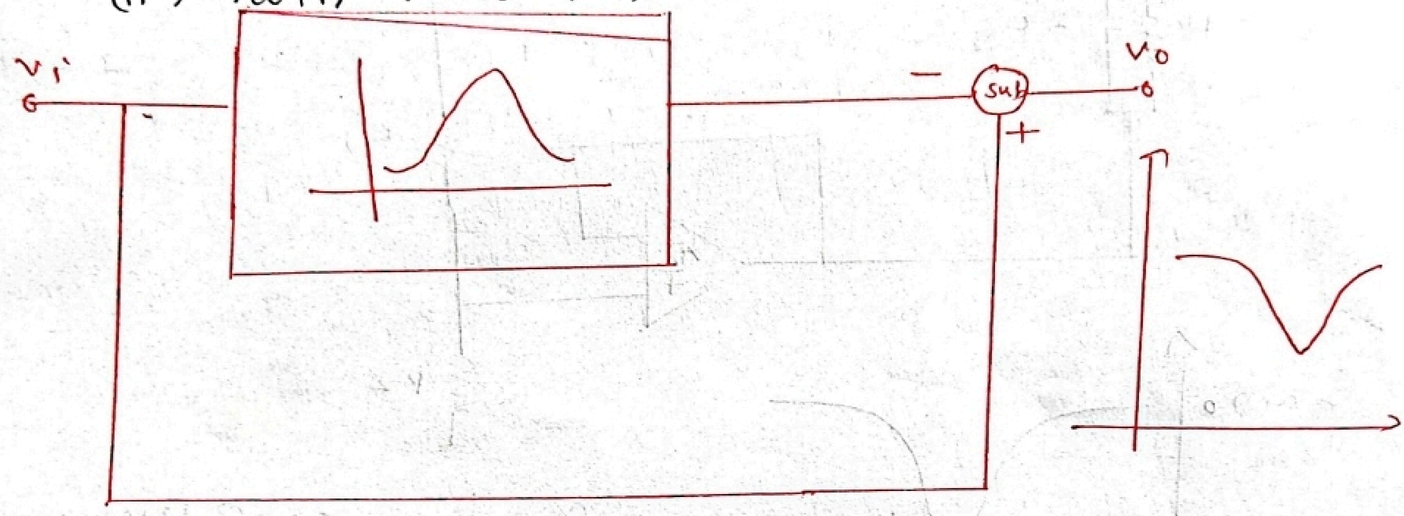
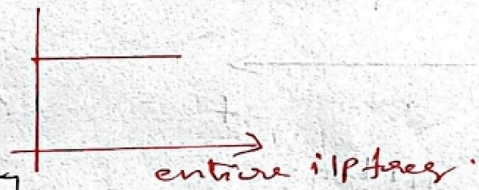
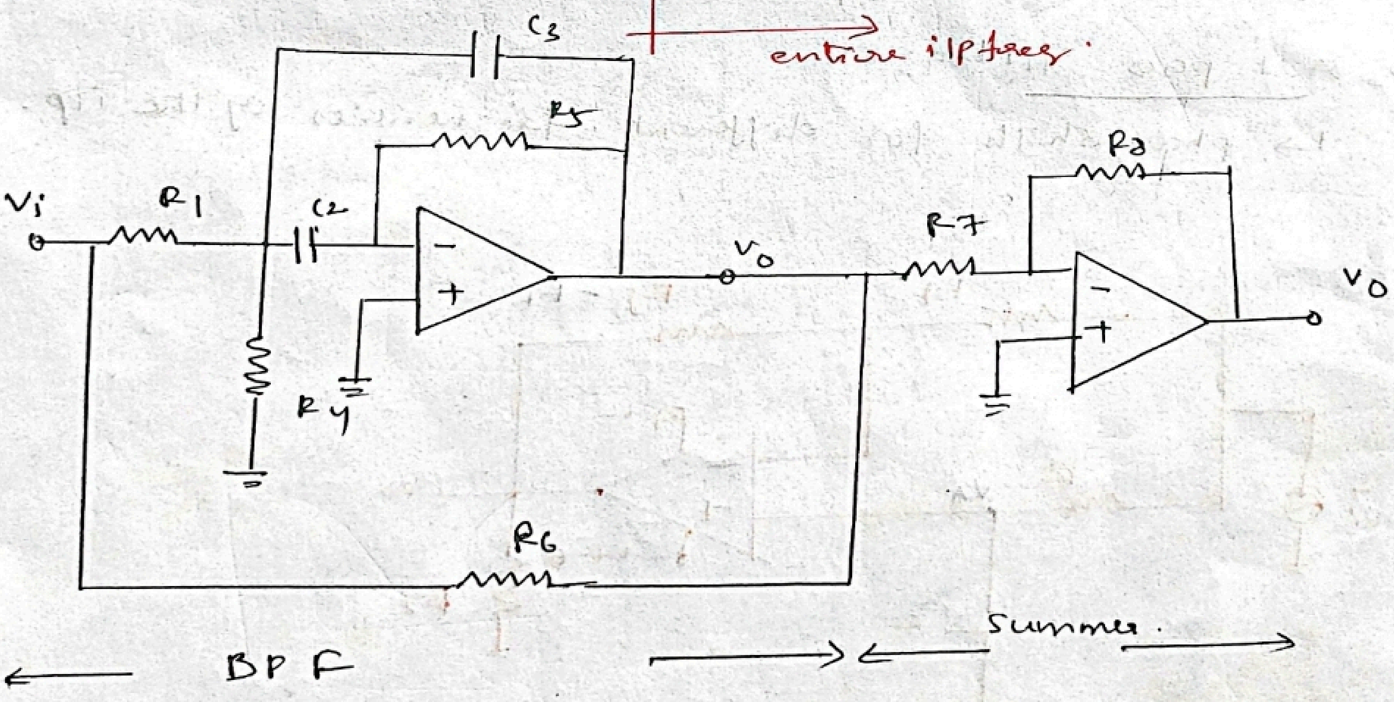
→ **NBRF:-** Notch filter used in communications biomedical instruments, to eliminate undesired frequencies.

→ They are also useful for rejection of one single frequency 50 Hz or 60 Hz, power line freq hum.

→ Two techniques – (i) Subtract the BPF o/p from its i/p
(ii) Twin T-notch filter.







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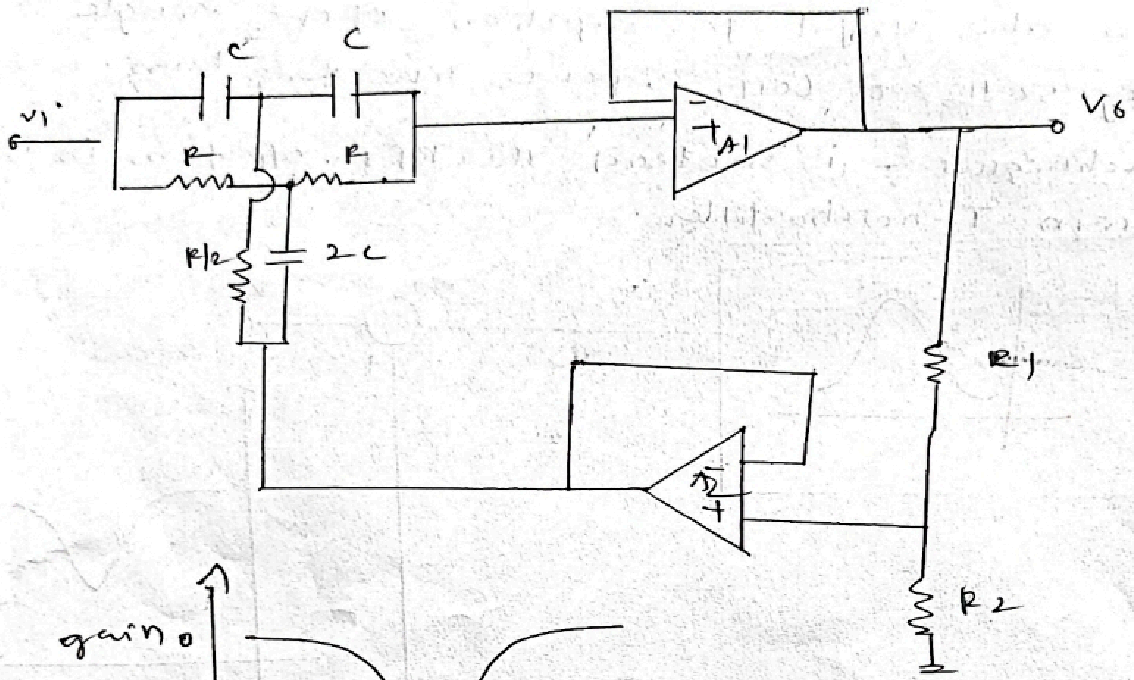
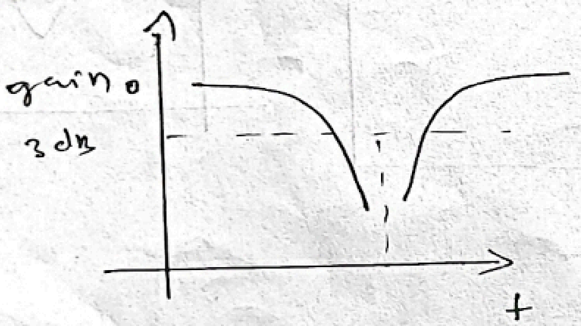
→ Twin-T notch filter :-

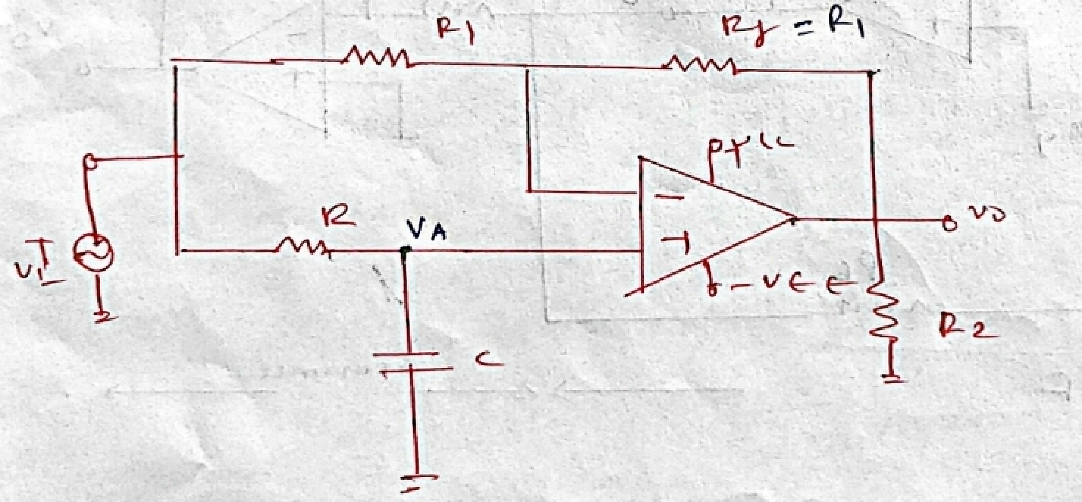




$Q = \frac{f_0}{B.W}$ as Q becomes very large B.W approaches 0.

→ All pass filter :-

↳ phase shifts for different frequencies of the i/p.



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→ when signals are transmitted over transmission lines, such as telephone wires, they undergo change in phase.

→ To compensate for these phase changes, all-pass filters are required. These are also called delay-equalizers or phase correctors.

→ By superposition theorem
assume i/p to the '+' terminal zero.
The ckt acts as inverting Ampr.

$$V_{o1} = -\frac{R_f}{R_1} V_{in}$$

$$V_{o1} = -V_{in} \quad \text{as } R_f = R_1$$

→ Now, assume i/p to the inverting terminal zero.
The circuit acts as a non-inverting Ampr.

$$V_{o2} = \left(1 + \frac{R_f}{R_1}\right) V_A$$

$$V_{o2} = 2 V_A \quad \text{as } R_f = R_1$$

vol. V_A by potential divider rule

$$V_A = V_{in}\left[\frac{X_C}{R + X_C}\right]$$

$$V_A = V_{in}\left[\frac{\frac{1}{j\omega C}}{R + \frac{1}{j\omega C}}\right]$$

$$V_A = V_{in}\left[\frac{1}{1 + j2\pi fRC}\right]$$

$$V_{o2} = 2 \cdot V_{in}\left[\frac{1}{1 + j2\pi fRC}\right]$$

Hence, the total o/p vol.

$$V_o = V_{o1} + V_{o2}$$

$$= -V_{in} + 2V_{in}\left(\frac{1}{1 + j2\pi fRC}\right)$$

$$V_o = V_{in}\left[-1 + \frac{2}{1 + j2\pi fRC}\right]$$

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$$\frac{V_o}{V_{in}} = \frac{1 - j\,2\pi f R C}{1 + j\,2\pi f R C}$$

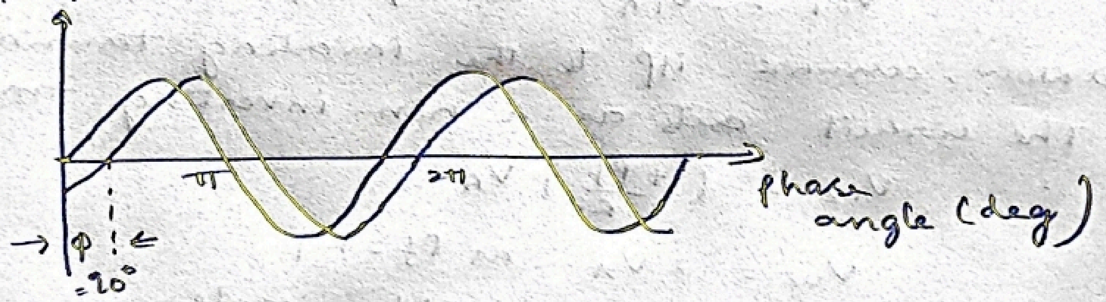
magnitude of transfer fun. is

$$\left|\frac{V_o}{V_{in}}\right| = \frac{\sqrt{1+(2\pi f R C)^2}}{\sqrt{1+(2\pi f R C)^2}} = 1$$

The o/p vol. V_o will have the same freq as the input, but lags V_i by 90°.

$$\phi = -\tan^{-1}(2\pi f R C) - \tan^{-1}(2\pi f R C)$$

$$= -2\tan^{-1}(2\pi f R C)$$



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

$R = 15.9\,k\Omega$, $C = 0.01\,\mu F$,

$\phi = -90^\circ$.

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