7. 10. 19.

Ch - 3
Operational Amplifiers

The OP-AMP -

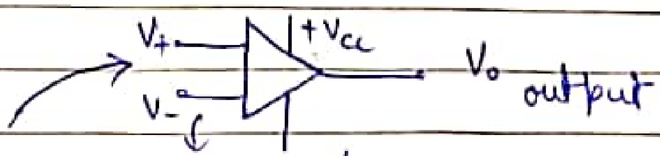
1) The OPAMP is essentially speaking, a voltage amplifier with very high gain.
2) Essentially, the OPAMP contains a large number of individual amplifier stages, interconnected.
3) The OPAMP circuitry contains a large number of Bipolar Junction Transistors (BJT'S), Field effect transistors (FET's), resistors etc.
4) The OPAMP circuitry occupies very little space and is hence suited to being made available in the Integrated Circuit (IC) form.
5) The OPAMP Circuitry, for the sake of ease of handeling, is contained in a large multi-pin package.

Characteristics of an Ideal OP-AMP -

1) Infinitely - large open loop gain.
2) Infinitely - large Input Impedence
3) Zero Output Impedence
4) Zero Input Current.

The OPAMP is capable of producing operations like addition, subtraction, multiplication, integration, differentiation etc. For each application, special circuitory needs to be designed.

The Symbol -



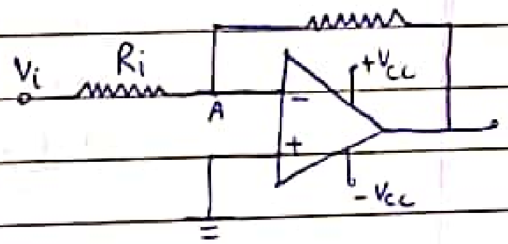
$V_d = V_+ - V_-$ — ① (Difference input)

$V_o = A[V_d] = A[V_+ - V_-]$

A = open loop gain (Between 10^5 & 10^6)

eg- Under ideal conditions, OPAMP's input I = 0

Also because A is large, $V_d \simeq 0$



In this case, since we gave grounded + terminal

$V_+ = 0$ — ③

$V_- \simeq 0$ — ④ Virtual ground concept

KCL at A

$$\frac{V_i}{R_i} + \frac{V_o}{R_f} = 0 \quad \text{— ⑤}$$

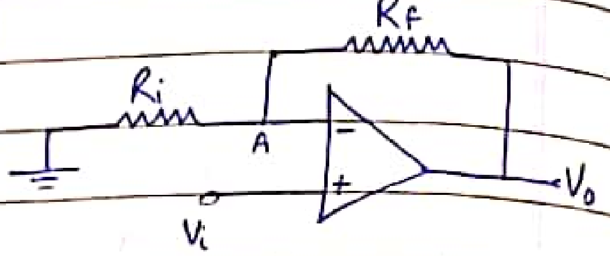
The actual gain

$$A_v \triangleq \frac{V_o}{V_i} \quad \text{— ⑥}$$

$$= \frac{-R_f}{R_i} \quad \text{— ⑦}$$

This is an example of inverting amplifier As output is negative to that of input

Example 2 - Non-inverting Amplifier



$V_F = V_i$ — ⑧

$V_i \approx V_i$ — ⑨

KCL at Ⓐ

$$\frac{V_i}{R_i} = -\left(\frac{V_i - V_o}{R_f}\right) \quad — ⑩$$

$$\therefore \quad A_V = \frac{V_o}{V_i}$$

$$= 1 + \frac{R_f}{R_i} \quad — ⑫$$

$$= 1 \quad (\text{if } R_f = 0)$$

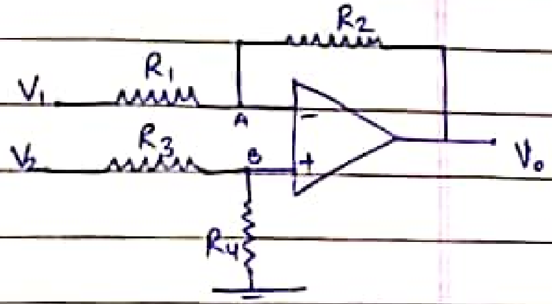
Q. Design a unity gain amplifier for
ⓐ Inverting application
ⓑ non-inverting application

Ans. ⓐ $|A_V| = 1$

$$A_V = -\frac{R_f}{R_i}$$

ⓑ $R_f = 0$

The Difference Amplifier



Because of the "virtual" short-circuit between + and - inputs of the OPAMP we write

$$V_A \simeq V_B \quad -①$$

KCL at A

$$\frac{V_1 - V_A}{R_1} = \frac{V_A - V_o}{R_2} \quad -②$$

KCL at B

$$\frac{V_2 - V_B}{R_3} = \frac{V_B}{R_4} \quad -③$$

By ①, ② & ③

$$V_o = -\frac{R_2}{R_1} V_1 + \left(\frac{R_4}{R_3 + R_4}\right)\left(\frac{R_1 + R_2}{R_1}\right) V_2 \quad -④$$

It is not easy to work out the gain of the circuit based on eq ④

Let us rewrite ④ as

$$V_o = -\alpha V_1 + \beta V_2 \quad -⑤$$

where $\alpha = \frac{R_2}{R_1}$ $-⑥$

and $\beta = \left(\frac{R_4}{R_3+R_4}\right)\left(\frac{R_1+R_2}{R_1}\right)$ $-⑦$

Special Case : If $\alpha = \beta$

$$V_o = \alpha (V_2 - V_1) \quad -⑧$$

We define the operation of the circuit in terms of the following two inputs -

a. Differential Input - When V_1 and V_2 are simultaneously present and have 180° phase difference between them.

b. Common Mode Input - When V_1 and V_2 are simultaneously present and have zero phase shift between them.

The differential input is defined as

$$V_d = V_2 - V_1 \quad -(9)$$

and common mode input is defined as

$$V_{cm} = \frac{V_2 + V_1}{2} \quad -(10)$$

$$V_2 = \frac{V_d + 2V_{cm}}{2} \quad -(11) \qquad V_1 = \frac{2V_{cm} - V_d}{2} \quad -(13)$$

Using (10) & (11) in (5) we get

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

Differential Gain — Common - Mode Gain

where

$$A_d = \frac{1}{2}\left[\frac{R_2}{R_1} + \left(\frac{R_4}{R_3+R_4}\right)\left(\frac{R_1+R_2}{R_2}\right)\right] \quad -(14) = \frac{1}{2}(\alpha+\beta)$$

$$A_{cm} = \left(\frac{R_4}{R_3+R_4}\right)\left(\frac{R_1+R_2}{R_1}\right) - \frac{R_2}{R_1} \quad -(15) = \beta - \alpha$$

Common Mode Rejection Ratio (CMRR)

$$CMRR \triangleq \left| \frac{A_d}{A_{cm}} \right| \quad -(16)$$

In dB terms,

$$CMRR(dB) \triangleq 20 \log \left| \frac{A_d}{A_{cm}} \right| \quad -(17)$$

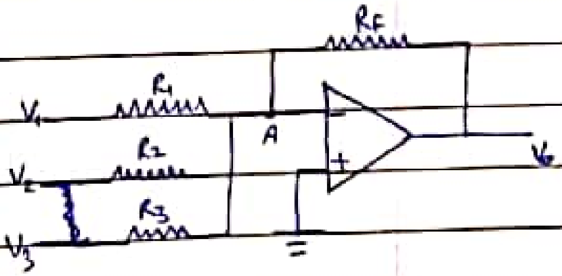
Prob 1. Define an OP Amp.

Q. Design an OP-Amp based Difference Amplifier with the output Voltage $V_0 = V_2 - 2V_1$ where V_1 & V_2 are the input voltage.

Ans $\alpha = \frac{R_2}{R_1} = 2$ $\beta = 1 \Rightarrow \frac{R_4}{R_3} = \frac{1}{2}$

Choose $R_1 = 1k\Omega = R_4$

Summing Amplifier



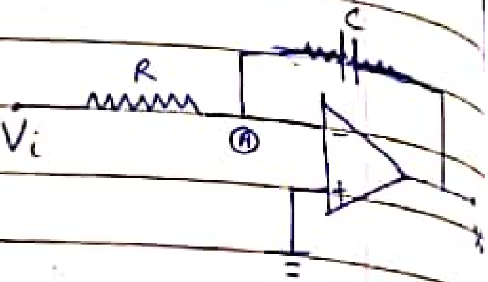
$V_A = 0 \quad -(1)$

KCL

$$\frac{V_1}{R_1} + \frac{V_2}{R_2} + \frac{V_3}{R_3} = \frac{-V_0}{R_f}$$

$$\Rightarrow V_0 = -\left[\frac{R_f}{R_1} V_1 + \frac{R_f}{V_2} V_2 + \frac{R_f}{V_3} V_3 \right] \quad -(2)$$

OPAMP - Based Integrator



KCL

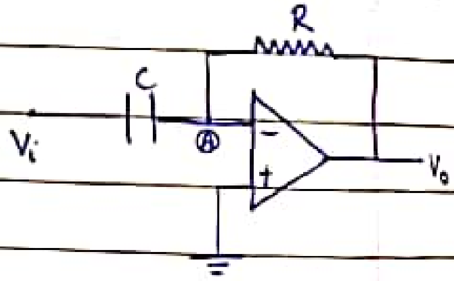
$V_A \approx 0$ — ①

$$\frac{V_i - 0}{R} = C\frac{d}{dt}[0 - V_0] = -C\frac{dV_0}{dt}$$

$$\therefore \quad V_i = -RC\frac{dV_0}{dt}$$

$$\Rightarrow \quad V_0 = \frac{-1}{RC}\int V_i\,dt \quad \text{— ②}$$

OPAMP - Based Differentiator



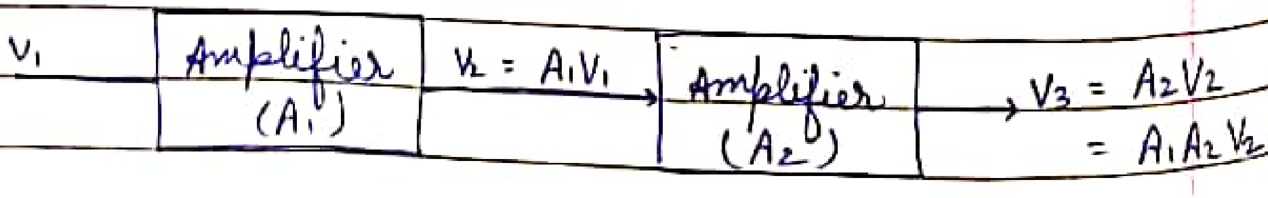
$V_A \approx 0$ — ①

KCL

$$C\frac{dV_i}{dt} = \frac{0 - V_0}{R} = \frac{-V_0}{R}$$

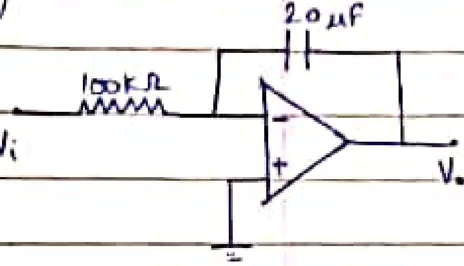
$$\therefore \quad V_0 = -RC\frac{dV_i}{dt} \quad \text{— ②}$$

Cascading of two (or more) circuits



for N cascaded circuits $V_0 = V_N = A_1 A_2 A_3 \ldots A_N V_i$

Q. For the circuit shown below, at $t=0$, V_{in} = D.C of 2.5 mV is applied. Find V_o for $t>0$.

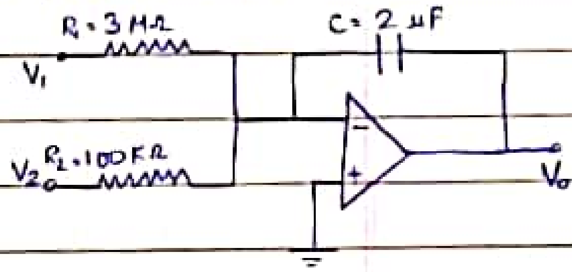


Ans. $RC = 10^5 \times 20 \times 10^{-6} = 2$ seconds

$$V_o = -\frac{1}{2}\int (2.5 \times 10^{-3})\, dt$$

$$= -1.25 \times 10^{-3}\, t \quad \text{Volts}$$

Q. Determine V_o in the circuit shown below. Assume that $V_1 = 10\cos 2t$ mV, $V_2 = 0.5t$ mV



Ans. $R_1 C = 6$ seconds

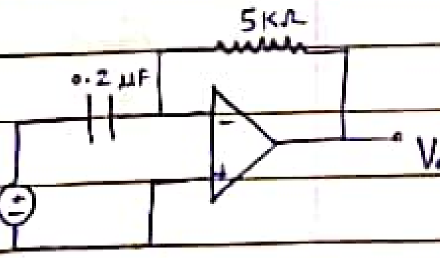
$R_2 C = 0.2$ second

$$V_o = \frac{-1}{R_1 C}\int V_1\, dt - \frac{1}{R_2 C}\int V_2\, dt$$

$$= \frac{-1}{6}[5\sin 2t] - \frac{1}{0.2}[0.25 t^2]$$

$$= -0.833 \sin 2t - 1.25t^2 \text{ mV}$$

Q. Sketch the output voltage with Time for the following circuit. Assume $V_o = 0$ at $t = 0$.



Ans. $0 \le t \le 2 \qquad V_i = 2t$

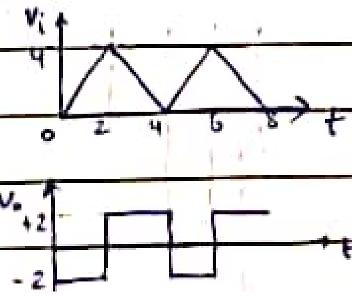
$V_i = a + bt$

At $t = 2$, $V = 4 \Rightarrow 4 = a + 2b$

At $t = 4$, $V = 0 \Rightarrow 0 = a + 4b$

$4 = -2b \Rightarrow b = -2$

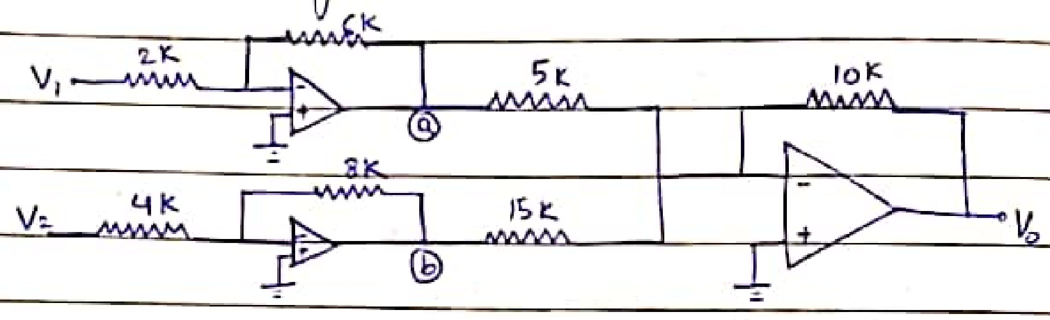
$a = 8$



$V_i = 8 - 2t$

$$V_o = -5\times10^{3}\times0.2\times10^{-6}\times -2$$
$$= -10^{-3}\times -2$$
$$= 2\times10^{-3}$$

Q. Calculate V_o for the circuits shown below.



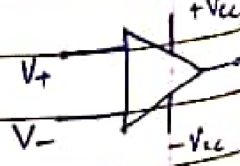
Ans. $V_a = -3V_1$, $V_b = -2V_2$

$$V_o = -\frac{10}{5}V_a - \frac{10}{15}V_b = \frac{30}{5}V_1 + \frac{20}{15}V_2$$

$$= \frac{1}{5}\left(30V_1 + \frac{20}{3}V_2\right)$$

Voltage Transfer Characteristic (VTC) of an OP-AMP

When an OP-AMP operates in open loop (i.e nothing connected between output and inputs), the output voltage is given by $V_o = AV_d$ —①



When the difference input V_d is written as $V_d = V_+ - V_-$ —②
and A is known as the open-loop gain. A typically lies between 10^5 and 10^6.

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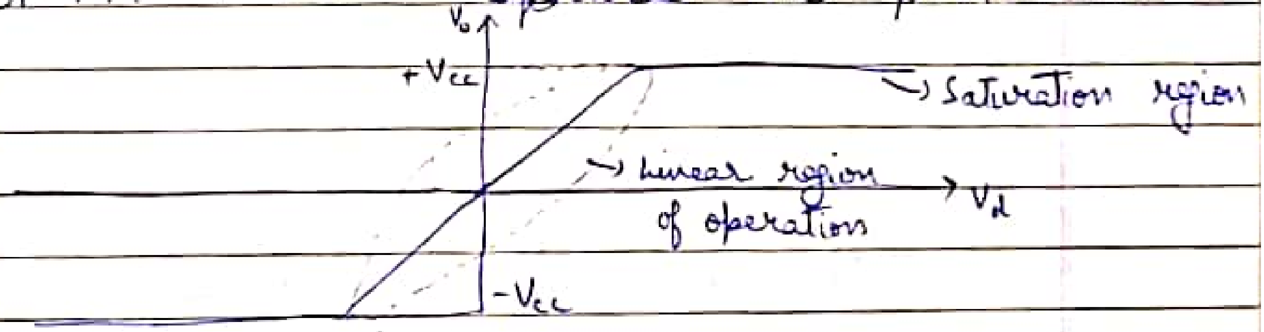
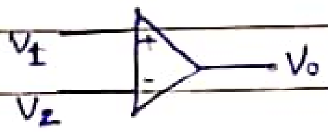
Since A is quite large, even an extremely small V_d can produce large V_o if we strictly go by eq. ①. In reality, however, the moment the magnitude of V_o exceeds that of V_{cc} the V_o value settles to a constant value $\simeq +V_{cc}$ or $-V_{cc}$, because of saturation of the semiconductor devices being used in the various amplifiers stages inside the OP-AMP. V.T.C captures this phenomenon.

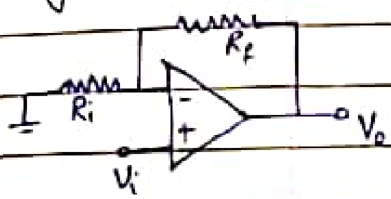


Comparator - Compares the input voltages (or two input currents) and produces a digital output whose value depends on which of the inputs has a larger magnitude.



If $V_1 > V_2$, $V_o = +V_{cc}$
If $V_1 < V_2$, $V_o = -V_{cc}$

Voltage Follower (also known as Buffer Amplifier) is nothing but a non-inverting amplifier with unity gain.



$A_v = 1 + \frac{R_f}{R_i}$

$= 1$ if $R_f = 0$

Output and input are quite isolated.

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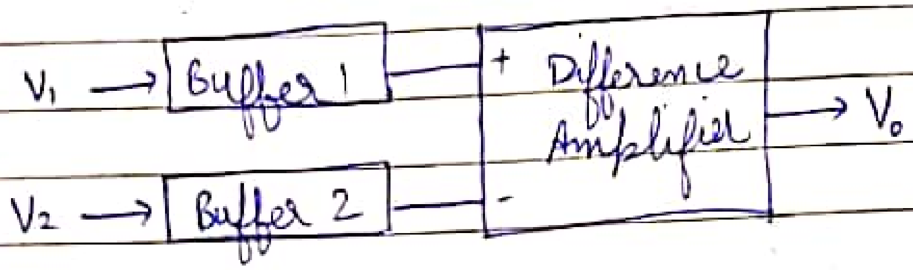
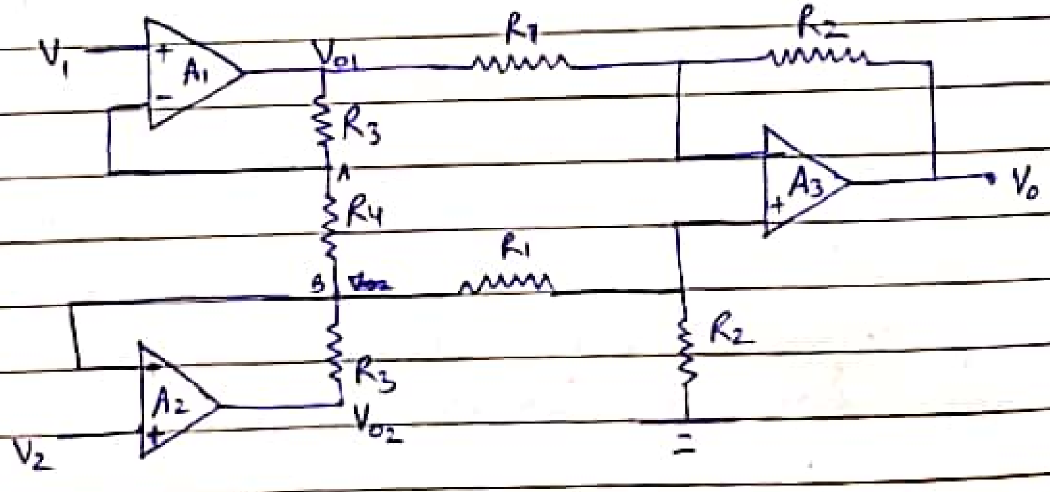
Instrumentation Amplifier



Advantages :-

1. High CMRR is possible
2. High Input Impedence
3. Good Sensitivity to small inputs

Detailed Circuit



$$V_o = A_d(V_{02} - V_{01}) + A_{cm}\left(\frac{V_{02} + V_{01}}{2}\right) \quad — ①$$

If $R_3' = R_1$, $R_4' = R_2$

$$A_d = \frac{1}{2}\left[\frac{R_2}{R_1} + \frac{R_4'}{R_3' + R_4'} \cdot \frac{R_1 + R_2}{R_1}\right] = \frac{R_2}{R_1}$$

$$A_{cm} = \frac{R_4'}{R_3' + R_4'} \cdot \frac{R_1 + R_2}{R_1} - \frac{R_2}{R_1} = 0$$

$$\Rightarrow V_o = \frac{R_2}{R_1}(V_{02} - V_{01}) \quad — ②$$

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$$I = \frac{V_{01} - V_{02}}{2R_3 + R_4} \quad — (3)$$

$$V_A = V_1 \quad — (4)$$

$$V_B = V_2 \quad — (5)$$

$$I = \frac{V_A - V_B}{R_4} = \frac{V_1 - V_2}{R_4} \quad — (6)$$

We should get

$$V_0 = \frac{R_2}{R_1}\left(\frac{2R_3 + R_4}{R_4}\right)(V_2 - V_1) \quad — (7)$$

Special Case -

Let $R_1 = R_2 = R_3 = R$ and let $R_4 = R_G$ (variable)

Then $V_0 = \frac{2R + R_G}{R_G}(V_2 - V_1)$

$$= \left[1 + \frac{2R}{R_G}\right](V_2 - V_1) \quad — (8)$$

Q. For the I.A already considered, $R_1 = R_2 = R_3 = 10k\Omega$, $V_1 = 2.011V$, $V_2 = 2.017V$ and $R_G = 500\Omega$. Calculate V_0.

Ans. Gain $= 1 + \frac{2R}{R_G} = 1 + \frac{2 \times \cancel{10}^{2} \times 10^3}{\cancel{500}} = 41$

$V_2 - V_1 = 6mV$

$V_0 = 41 \times 6 \times 10^{-3}$

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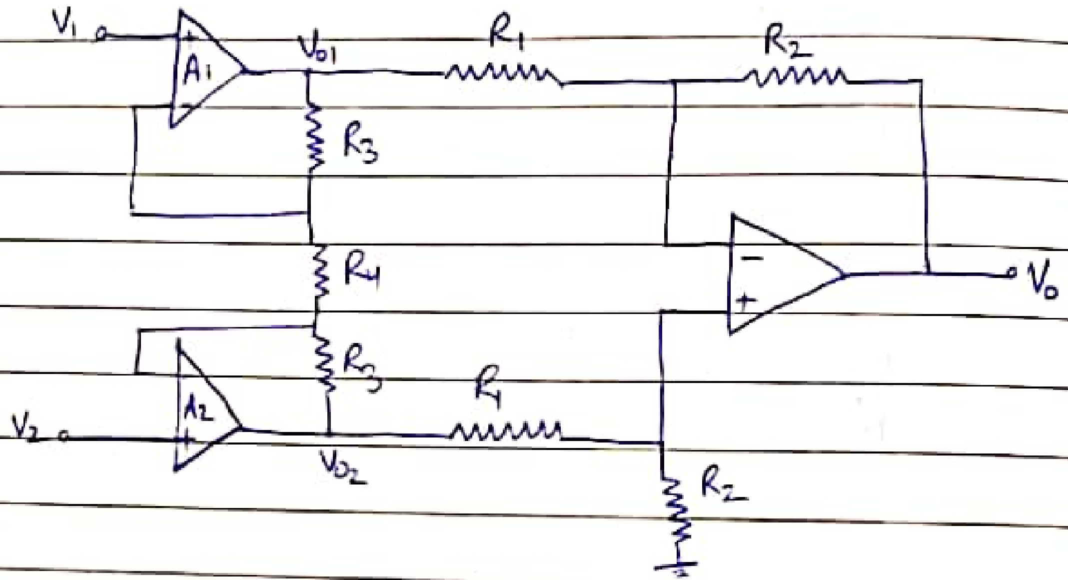
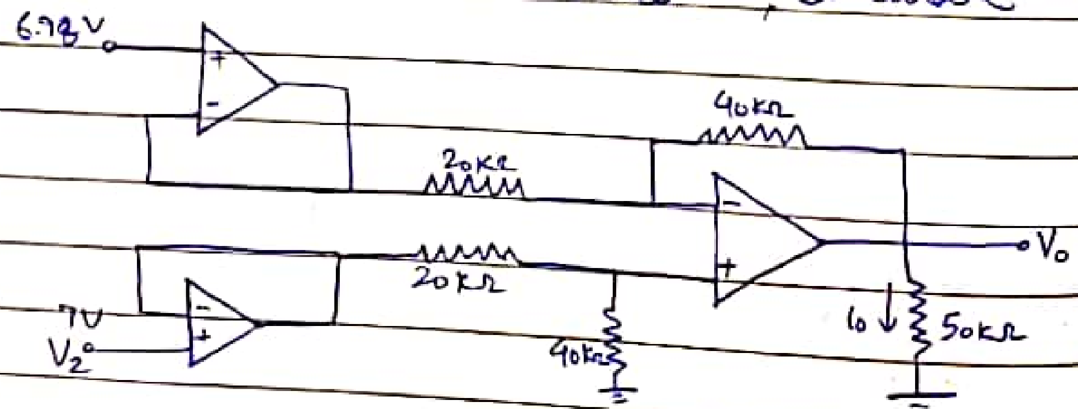
Instrumentation Amplifier Circuit



$$V_o = \frac{R_2}{R_1}\left(1 + \frac{2R_3}{R_4}\right)(V_2 - V_1)$$

Q. In the circuit shown below, calculate V_o & i_o



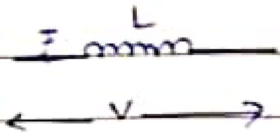
Ans. $R_1 = 20k\Omega$ $R_2 = 40k\Omega$ $R_3 = 0$ $R_4 = \infty$

$V_1 = 6.98V$ $V_2 = 7V$

$\therefore$ $V_o = 40mV$

$i_o = \dfrac{40 \times 10^{-3}}{50 \times 10^{3}} A$

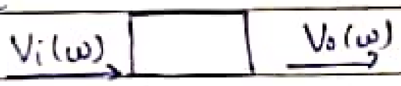
$= 0.8 \mu A$

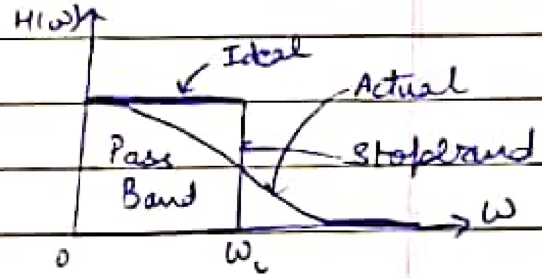


$V = j\omega L I$
$Z = j\omega L$
$Z = jX_L$

$V = ZI$
$Z = \frac{-j}{\omega C} = \frac{1}{j\omega C}$

Low Pass Filter



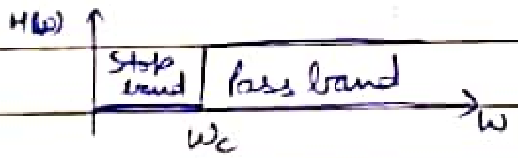


Transfer Function

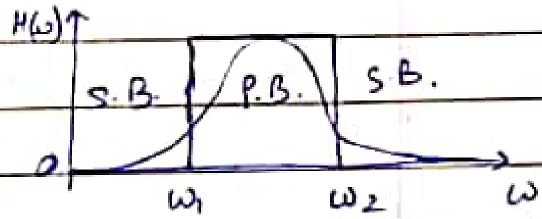
$H(\omega) \triangleq \frac{V_o(\omega)}{V_i(\omega)}$ —①

ω_c = Cutoff Angular Freq.

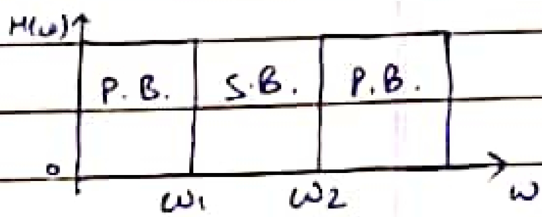
High Pass Filter (HPF)



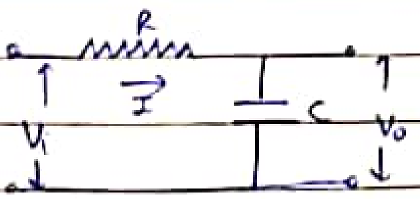
Band Pass Filter (BPF)



Band Stop Filter (BSF)



Ex-1.



L.P.F.

$I = \frac{V_i}{Z_R + Z_C} = \frac{V_i}{R - \frac{j}{\omega C}} = \frac{V_i}{R + \frac{1}{j\omega C}}$ —①

$V_o = Z_C I = \frac{1}{j\omega C} \times \frac{V}{R + \frac{1}{j\omega C}}$

$$V_o = \frac{V_i}{1+j\omega RC} \quad -②$$

$$H(\omega) = \frac{V_o(\omega)}{V_i(\omega)} = \frac{1}{1+j\omega RC} \quad -③$$

$$|H(\omega)| = \frac{1}{\sqrt{1+\omega^2R^2C^2}} \quad -④$$

At $\omega = \omega_c$, $|H| = \frac{1}{\sqrt{2}}$ $\quad -⑤$

$$\therefore \frac{1}{\sqrt{2}} = \frac{1}{\sqrt{1+\omega_c^2R^2C^2}}$$

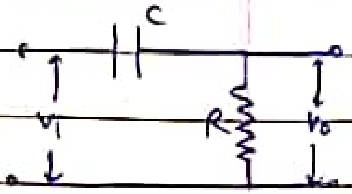
$$\therefore 2 = 1+\omega_c^2R^2C^2$$

$$\therefore \omega_c = \frac{1}{\sqrt{RC}} \quad -⑥ \qquad \therefore f_c = \frac{1}{2\pi\sqrt{RC}} \quad -⑦$$

Q. Using a $1\mu F$ capacitor design RC LPF for
ⓐ $f_c = 1\,MHz$ ⓑ $f_c = 1\,KHz$ ⓒ $f_c = 100\,MHz$

Ans. ⓐ $1\times10^6 = \frac{1}{2\pi R\times1\times10^{-6}}$, $R = \frac{1}{2\pi}$

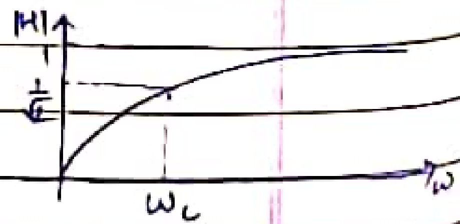
Q. Find $H(\omega)$?



Ans. $I = \frac{V_i}{R+1/j\omega C}$

$V_o = IR$

$$H(\omega) = \frac{R}{R+\frac{1}{j\omega C}} = \frac{j\omega RC}{R+j\omega RC}$$



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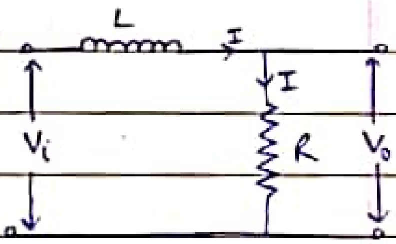
Filters examples 1 & 2 were of "RC Filter" category. They can also be termed "Passive" filters because to DC input is needed. They can also be termed "First-order" filters because the mathematical expression for $H(\omega)$ contains only ω terms (now 2 terms, now 3 terms, etc.)

Example-3 Passive First-Order RL Filters (LPF)

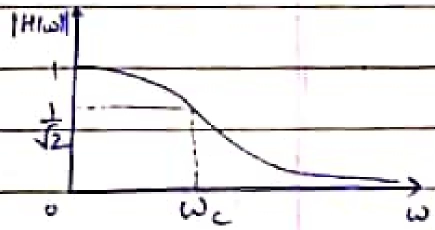
$$I = \frac{V_i}{R + j\omega L} \quad -①$$



$$V_o = RI = \frac{RV_i}{R + j\omega L} \quad -②$$

$$H(\omega) \triangleq \frac{V_o(\omega)}{V_i(\omega)} = \frac{R}{R + j\omega L}$$

$$\therefore H(\omega) = \frac{1}{1 + \frac{j\omega L}{R}} \quad -③$$



$$\therefore |H(\omega)| = \frac{1}{\sqrt{1 + \frac{\omega^2 L^2}{R^2}}} \quad -④$$

At cutoff,

$$\frac{1}{\sqrt{2}} = \frac{1}{\sqrt{1 + \frac{\omega^2 L^2}{R^2}}}$$

$$\therefore 2 = 1 + \frac{\omega^2 L^2}{R}$$

$$\Rightarrow \omega_c = \frac{R}{L} \quad -⑤ \qquad \therefore f_c = \frac{R}{2\pi L} \quad -⑥$$

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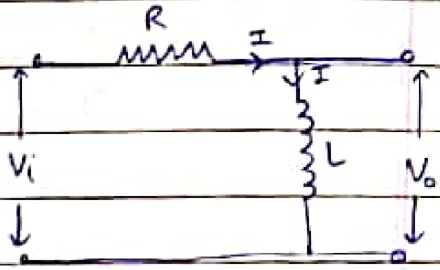
Example-4 Passive First-Order Filter (HPF)

$$I = \frac{V_i}{R + j\omega L} \quad —(1)$$



$$V_o = j\omega L I$$

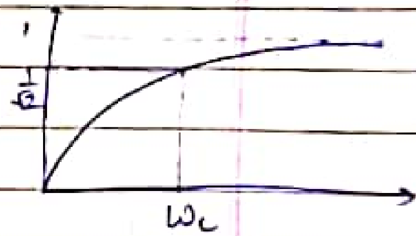
$$= \frac{j\omega L V_i}{R + j\omega L} \quad —(2)$$

$$\therefore H(\omega) \triangleq \frac{V_o(\omega)}{V_i(\omega)} = \frac{j\omega L}{R + j\omega L} \quad —(3)$$

$$\therefore |H(\omega)| = \frac{\omega L}{\sqrt{R^2 + \omega^2 L^2}} = \frac{1}{\sqrt{1 + \left(\frac{R}{\omega L}\right)^2}} \quad —(4)$$

At cutoff

$$\frac{1}{\sqrt{2}} = \frac{1}{\sqrt{1 + \frac{R^2}{\omega_c^2 L^2}}}$$



$$\therefore 2 = 1 + \frac{R^2}{\omega_c^2 L^2}$$

$$\Rightarrow \omega_c = \frac{R}{L} \quad —(5) \qquad \therefore f_c = \frac{R}{2\pi L} \quad —(6)$$

Q. For R-L LPF, if $L = 3\,\mu H$, what R is need to obtain $f_c = 350\ kHz$?

Ans. ~~13.19 Ω~~ 6.6 Ω

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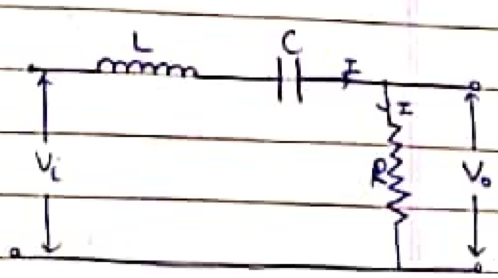
Example-5. **Second-order Passive Filter**

$$I = \frac{V_i}{R + j\omega L - \frac{j}{\omega C}} \quad \text{—(1)}$$

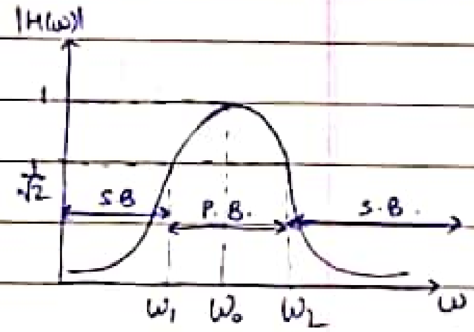


$$V_o = RI \quad \text{—(2)}$$

$$V_o = \frac{RV_i}{R + j\left(\omega L - \frac{1}{\omega C}\right)}$$

$$\therefore H(\omega) \triangleq \frac{V_o(\omega)}{V_i(\omega)} = \frac{R}{R + j\left(\omega L - \frac{1}{\omega C}\right)} \quad \text{—(2)}$$

$$= \frac{1}{1 + j\left(\frac{\omega L - \frac{1}{\omega C}}{R}\right)} \quad \text{—(3)}$$



$$|H(\omega)| = \frac{1}{\sqrt{1 + \left(\frac{\omega L - \frac{1}{\omega C}}{R}\right)^2}} \quad \text{—(4)}$$

ω_0 = Center frequency
= Resonance frequency
= Design frequency

At cutoff

$$\frac{1}{\sqrt{2}} = \frac{1}{\sqrt{1 + \left(\frac{\omega L - \frac{1}{\omega C}}{R}\right)^2}} \quad \text{—(4)}$$

At resonance, $\omega = \omega_0$ and $|H(\omega)| = 1$

$$\therefore \omega_0 L = \frac{1}{\omega_0 C} \Rightarrow \omega_0 = \frac{1}{\sqrt{LC}} \quad \text{—(5)}, \quad f_0 = \frac{1}{2\pi\sqrt{LC}} \quad \text{—(6)}$$

$$2 = 1 + \frac{\left(\omega L - \frac{1}{\omega C}\right)^2}{R^2} \Rightarrow \left(\omega L - \frac{1}{\omega C}\right)^2 = R^2$$

$$\omega^2L^2 + \frac{1}{\omega^2C^2} - \frac{2L}{C} = R^2 \quad -(7)$$

This is a fourth order equation
The two non-negative solutions to eq. (7) have been shown to be

$$\omega_1 = \frac{-R}{2L} + \sqrt{\left(\frac{R}{2L}\right)^2 + \frac{1}{LC}} \quad -(8)$$

and $$\omega_2 = \frac{+R}{2L} + \sqrt{\left(\frac{R}{2L}\right)^2 + \frac{1}{LC}} \quad -(9)$$

Bandwidth is that range of ω ($\&$ f) over which the filter's performance is considered to be good enough.

$\therefore$ Bandwidth $B \triangleq \omega_2 - \omega_1 \quad -(10)$

$$= \frac{R}{L} \quad -(11)$$

Relative Bandwidth

$$R.B.W. \triangleq \frac{\omega_2 - \omega_1}{\omega_0} \quad -(12)$$

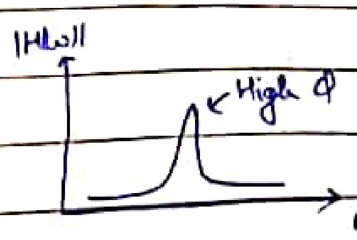
Quality Factor

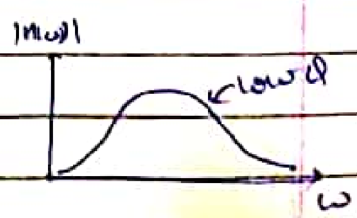
$$Q = \frac{\omega_0 L}{R} \quad -(14)$$

$$Q = \frac{\omega_0}{\omega_2 - \omega_1} = \frac{\omega_0}{B.W.} \quad -(15)$$

Percentage Bandwidth

$$P.B.W. = 100 \times \frac{\omega_2 - \omega_1}{\omega_0} \quad -(13)$$





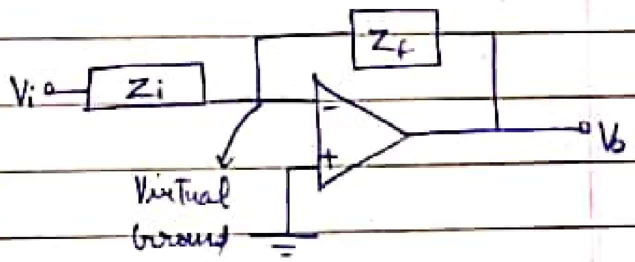
Q. For the RLC BPF, $L = 3\mu H$, $C = 3\mu F$. Calculate f_0. What R value is needed to obtain $Q = 50$?

Ans $f_0 = \dfrac{1}{2\pi\sqrt{LC}} = \dfrac{10^6}{2\pi \times 3}$ Hz

$R = \dfrac{\omega_0 L}{Q} = \dfrac{1}{50}\ \Omega$

Active Filters Using OP-AMP's

(a) Inverting Mode :-

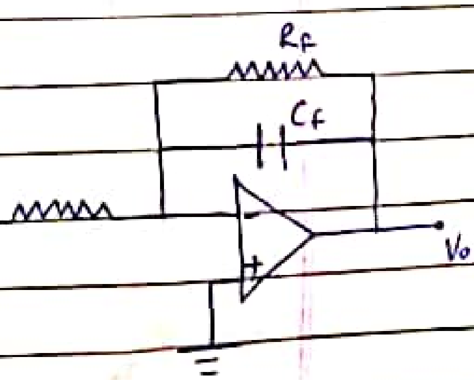


$$\frac{V_i}{Z_i} = \frac{-V_o}{Z_f} \quad \text{—(1)}$$

$$\therefore H(\omega) \triangleq \frac{V_o(\omega)}{V_i(\omega)}$$

$$= -\frac{Z_f}{Z_i} \quad \text{—(2)}$$

Example-1. Active LPF



$$\frac{1}{Z_f} = \frac{1}{R_f} + \frac{1}{[1/j\omega C_f]}$$

$$Z_f = \frac{R_f \times \frac{1}{j\omega C_f}}{R_f + \frac{1}{j\omega C_f}}$$

$$= \frac{j\omega C_f R_f}{1 + j\omega C_f R_f} \quad \text{—(3)}$$

$$Z_i = R_i \quad -④$$

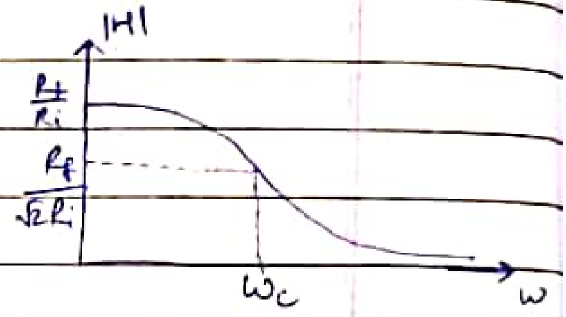
$$H_1(\omega) = -\frac{R_f}{R_i}\left[\frac{1}{1+j\omega R_f C_f}\right] \quad -⑤$$

$\frac{R_f}{R_i} \triangleq$ D.C. Gain

$$|H(\omega)| = \left[\frac{R_f}{R_i}\right]\left[\frac{1}{\sqrt{1+\omega^2 R_f^2 C_f^2}}\right] \quad -⑥$$

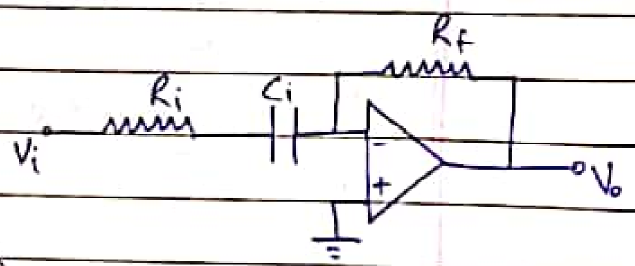
$$\omega_c = \frac{1}{R_f C_f} \quad -⑦$$

$$f_c = \frac{1}{2\pi R_f C_f} \quad -⑧$$



Cutoff Angular Freq. (Carrier Angular Freq.)

Example-2 Active HPF

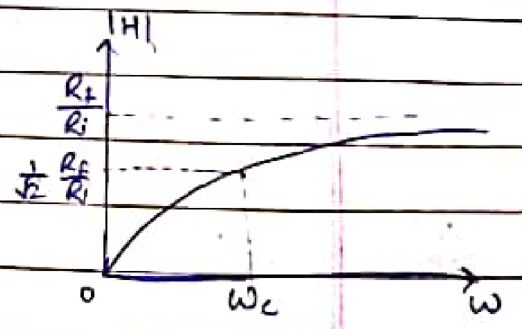


$$H(\omega) \triangleq \frac{V_o(\omega)}{V_i(\omega)}$$

$$= -\underbrace{\left(\frac{R_f}{R_i}\right)}_{\text{D.C. Gain}}\left(\frac{j\omega C_i R_i}{1+j\omega C_i R_i}\right) \quad -①$$

$$|H(\omega)| = \frac{R_f}{R_i}\frac{\omega C_i R_i}{\sqrt{1+\omega^2 C_i^2 R_i^2}}$$

$$= \frac{R_f}{R_i}\left[\frac{1}{\sqrt{1+\frac{1}{\omega^2 C_i^2 R_i^2}}}\right] \quad -②$$



$$\omega_c = \frac{1}{R_i C_i} \quad -③$$

Q. Design an inverting LPF (active) with a D.C Gain = 4 and Carrier freq. = 500Hz, $C_f = 0.1\ \mu F$

Ans. $\omega_c = \frac{1}{R_f C_f} = 2\pi 500 = \frac{1}{R_f \cdot .01\times 10^{-7}}$

$R_f = \frac{1}{2\pi \times 500 \times 10^{-7}} = 3.18\ k\Omega$

$R_i = \frac{R_f}{4} = \frac{3.18}{4}\ k\Omega$

8. Design an inverting active HPF with a gain of 5 and $f_c = 2$ KHz. Use $0.1\mu F$ capacitor.

Ans. $f_c = \frac{1}{2\pi R_i C_f} \Rightarrow R_i = \frac{1}{2\pi \times 2000 \times 1\times 10^{-7}} = 0.796\ k\Omega$

$R_f = 5R_i = 0.398\ k\Omega$

Active Non-Inverting Filters

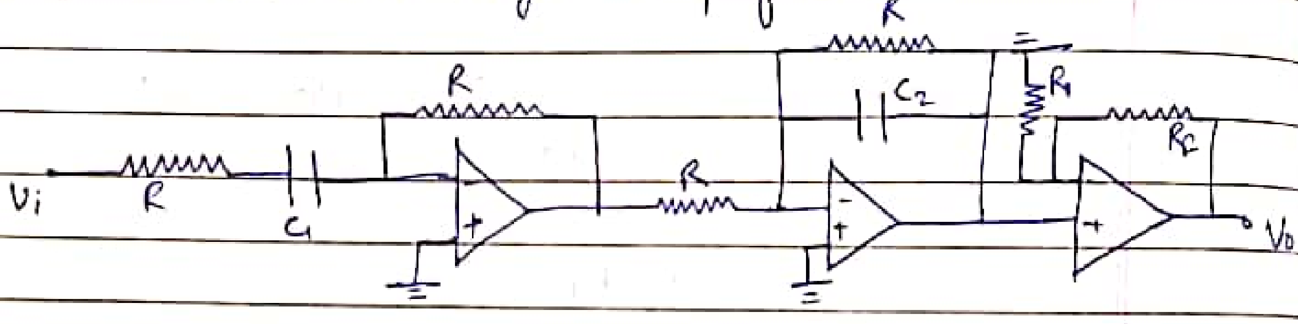
1) Cascade a known inverting design with an inverting amplifier having unity Gain.
2) Use a passive design and cascade it with a non-inverting amplifier having the designed gain.

$V_i \rightarrow$ [Passive LPF/HPF] $\rightarrow$ [Non-Inverting Amplifier with required gain] $\rightarrow V_o$

Band Pass Filters (BPF) can be obtained by cascading a suitably designed HPF with a suitably-designed LPF.

Band Stop Filters can also be designed using LPF & HPF combinations

Active BPF using the cascade of HPF, LPF, and Non-Inverting Amplifier



$$H(\omega) = \left[\frac{-j\omega R C_1}{1+j\omega R C_1}\right]\cdot\left[\frac{-1}{1+j\omega R C_2}\right]\cdot\left[1+\frac{R_f}{R_1}\right] \quad -①$$

$$|H(\omega)| = \left(1+\frac{R_f}{R_1}\right)\left[\frac{\omega R C_1}{\sqrt{1+\omega^2R^2C_1^2}\,\sqrt{1+\omega^2R^2C_2^2}}\right] \quad -②$$

$$= \frac{1+R_f/R_1}{\sqrt{1+\frac{1}{\omega^2R^2C_1^2}}\,\sqrt{1+\omega^2R^2C_2^2}} \quad -③$$

$$\omega_1 \triangleq \frac{1}{RC_1} \quad -④ \qquad \omega_2 \triangleq \frac{1}{RC_2} \quad -⑤$$

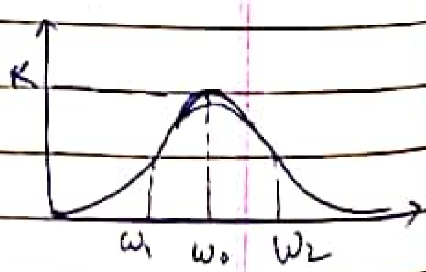
For max $|H(\omega)|$

$$\frac{d\,|H(\omega)|}{d\omega} = 0 \quad -⑥$$

$$\frac{d}{d\omega}\left[\frac{1}{\sqrt{f_1 f_2}}\right] = 0 \quad -⑦$$

When $f_1 \triangleq 1 + \frac{1}{\omega^2R^2C_1^2}$ —⑧

$f_2 \triangleq 1+\omega^2R^2C_2^2$ —⑨



K = Passband gain

ω_0 = Center Angular Freq

(Resonance Angular Freq)

Yield

$$\frac{d}{d\omega}\left[(f_1 f_2)^{-1/2} \right] = 0$$

$$\Rightarrow \quad -\frac{1}{2} (f_1 f_2)^{-3/2} \frac{d}{d\omega}(f_1 f_2) = 0$$

Since $f_1 f_2 \neq 0$ we get

$$\frac{d}{d\omega}(f_1 f_2) = 0 \quad — (10)$$

$$f_1 \frac{df_2}{d\omega} + f_2 \frac{df_1}{d\omega} = 0 \quad — (11)$$

$$\frac{df_1}{d\omega} = \frac{-2}{RC_1^2 \omega^2}$$

$$\omega_0 = \frac{1}{R\sqrt{C_1 C_2}} \quad — (14)$$

$$= \frac{1}{\sqrt{RC_1}\sqrt{RC_2}} = \sqrt{\omega_1 \omega_2} \quad — (15)$$

We define $f_1 = \frac{\omega_1}{2\pi}$

Passband Gain

$$|H(\omega)| = \frac{1 + R_f / R_1}{\sqrt{1 + \frac{1}{\omega^2 R^2 C_1^2}} \sqrt{1 + \omega^2 R^2 C_2^2}}$$

$$K = 1 + R_f / R$$

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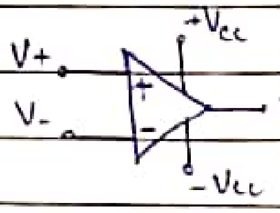
Comparator circuit using an OP-AMP in open loop.



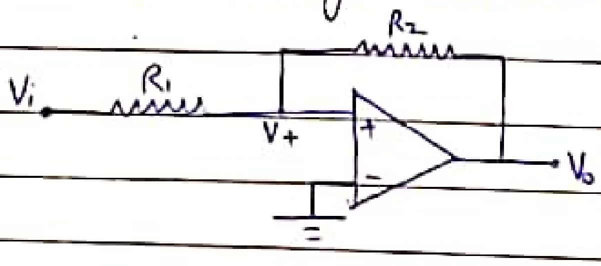
$V_o = +V_{cc}$ (HIGH) for $V_+ > V_-$

$= -V_{cc}$ (LOW) for $V_+ < V_-$

Disadvantage - Even for a small change in input (caused by say random noise signals), the output can switch from one state to another in quite an unpredictable fashion (random behaviour).

Schmitt Trigger : is a comparator circuit which uses ~~possible~~ positive feedback to make the output more predictable.

Non - Inverting Schmitt Trigger :



we deliberately make V_+ high enough & low enough

KCL

$$\frac{V_i - V_+}{R_1} + \frac{V_o - V_+}{R_2} = 0 \quad -(1)$$

$$V_+\left[\frac{1}{R_1} + \frac{1}{R_2}\right] = \frac{V_i}{R_1} + \frac{V_o}{R_2}$$

$$V_+\left[\frac{R_1 + R_2}{R_1 R_2}\right] = \frac{V_i}{R_1} + \frac{V_o}{R_2}$$

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$$V_+ = \left[\frac{R_2}{R_1+R_2}\right] V_i + \left[\frac{R_1}{R_1+R_2}\right] V_0 \quad — ②$$

Ⓐ Let us assume that, in the beginning, output is HIGH that is $V_0 = +V_{cc}$. Then eq ② becomes

$$V_+ = \left[\frac{R_2}{R_1+R_2}\right] V_i + \left[\frac{R_1}{R_1+R_2}\right] V_{cc} \quad — ③$$

The output will always switch to the other state when V_+ crosses 0 in either direction. For $V_+ = 0$ eq ③ yields

$$V_i = -\frac{R_1}{R_2} V_{cc} \quad — ④$$

We define a Threshold voltage V_{Th} by

$$V_{Th} = \frac{R_1}{R_2} V_{cc} \quad — ⑤$$

so that eq. ④ can be written as $V_i = -V_{Th}$ — ⑥

Ⓑ If V_i falls below $-V_{Th}$ the output would switch to low, i.e. $V_0 = -V_{cc}$

Then eq ② will yield

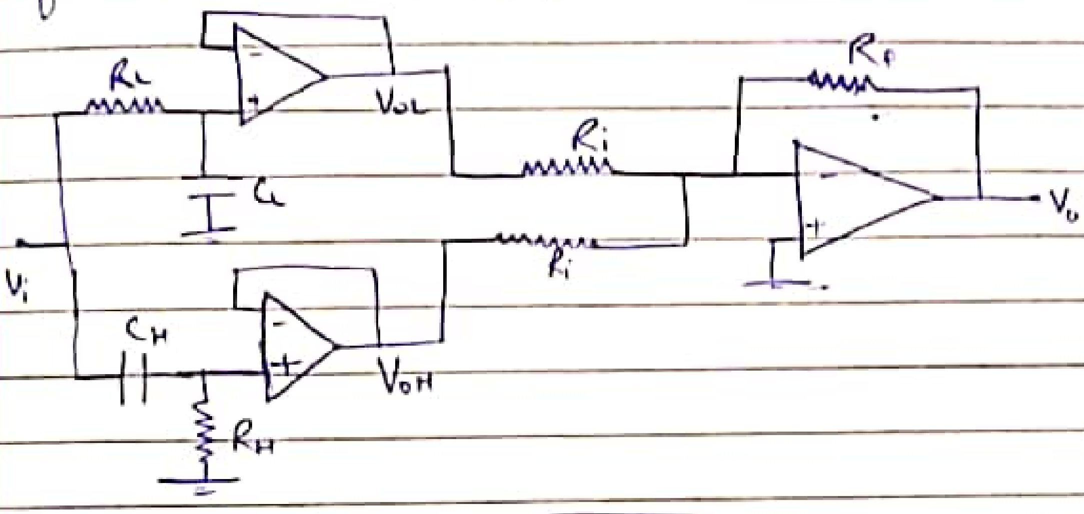
$$V_+ = \left(\frac{R_2}{R_1+R_2}\right) V_i - \left(\frac{R_1}{R_1+R_2}\right) V_{cc} \quad — ⑦$$

Hence the output will now switch at

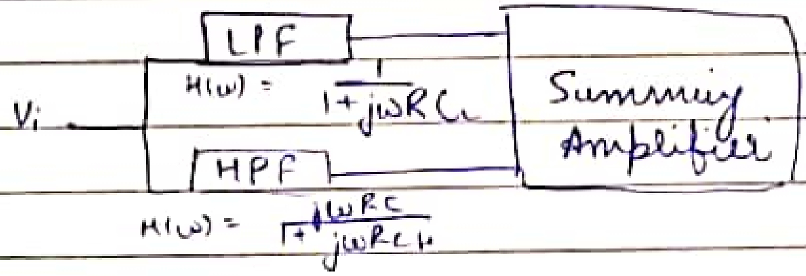
$V_{in} = +V_{Th}$ — ⑧

Ⓒ This sequence can continue

Q. Determine the transfer function and nature of the Active filter



Ans.



$$V_{oL} = \frac{V_i}{1+j\omega R_L C_L} \quad -① $$

$$V_{oH} = \frac{j\omega R_H C_H V_i}{1+j\omega R_H C_H} \quad -② $$

$$V_o = \frac{-R_f}{R_i}\left[\frac{1}{1+j\omega R_L C_L} + \frac{j\omega R_H C_H}{1+j\omega R_H C_H}\right]V_i \quad -③ $$

$$H(\omega) = \frac{V_o(\omega)}{V_i(\omega)}$$

$$= -\frac{R_f}{R_i}\left[\frac{1}{1+j\omega R_L C_L} + \frac{1}{1-\frac{j}{\omega R_H C_H}}\right] \quad -④ $$

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