Introduction:

→ Feedback plays a very important role in electronic circuits and the basic parameters such as input impedance, output impedance, current & voltage gain and bandwidth may be altered considerably by the use of feedback for a given amplifier.

→ In large signal amplifiers and electronic measuring instruments, the major problem of distortion should be avoided as far as possible.

→ Again, the gain must be independent of external factors such as variation in the voltage of the d.c supply and of the values of the circuit components.

→ All this can be achieved by feedback. A portion of the output signal is taken from the output of the amplifier and is combined with the normal input signal and thereby the feedback is accomplished.

Concept Feedback:

→ A block diagram of an amplifier with feedback is as shown in figure.

→ The output quantity (either voltage or current) is sampled by a suitable sampler which is of two types, namely, voltage sampler and current sampler, and fed to the feedback network

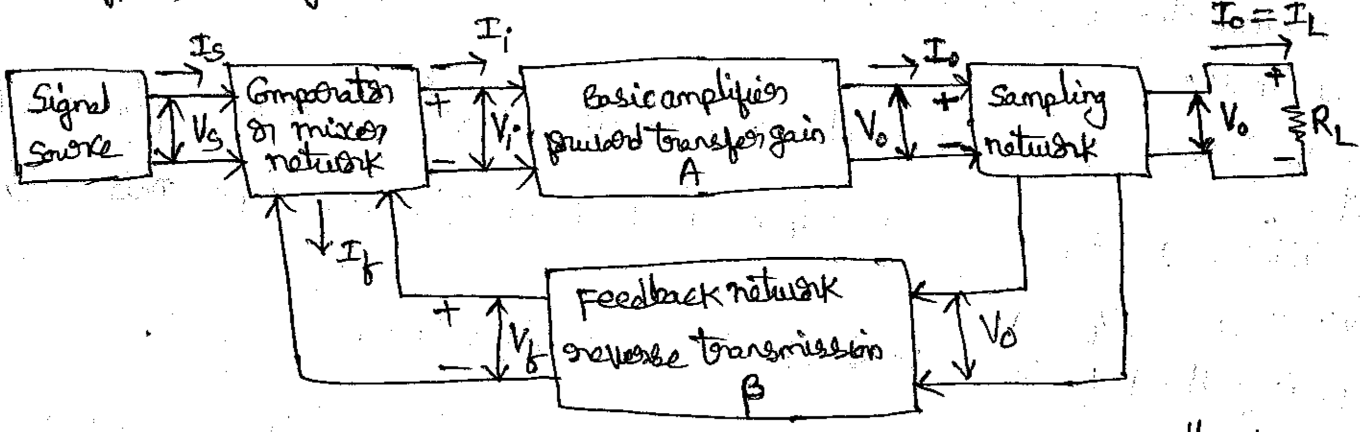


Fig: Block diagram of an amplifier with feedback.

→ The output of feedback network which has a fraction of the output signal is combined with external source signal V_s through a mixer and fed to the basic amplifier.

→ Mixer, also known as comparator, is of two types, namely, series mixer and shunt mixer.

→ The different blocks of the amplifier are,

(i) Comparator or mixer network
(ii) Basic amplifier forward transfer gain
(iii) Sampling network
(iv) Feedback network reverse transmission

$A_V = \frac{V_o}{V_i}$ = Voltage gain of basic amplifier (without f/b)

$A_I = \frac{I_o}{I_i}$ = Current gain of basic amplifier (without f/b)

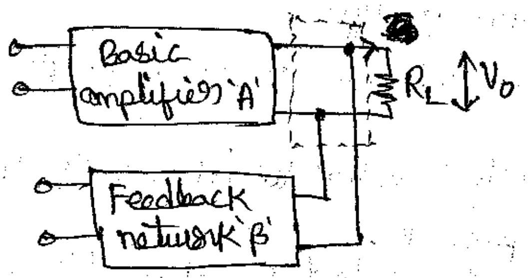
β = feedback ratio = V_f/V_o

$A_{Vf} = \frac{V_o}{V_s}$ = Voltage gain of f/b amplifier

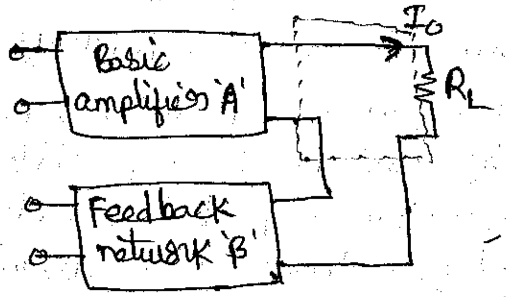
$A_{If} = \frac{I_o}{I_s}$ = Current gain of f/b amplifier.

Sampling Network:

→ There are two ways to Sample the output, according to the Sampling parameter, either Voltage or Current.



Fig(a): Voltage or node Sampling.



Fig(b): current or loop Sampling.

→ The output voltage is sampled by connecting the feedback network in shunt across the output as shown in figure (a).
This type of connection is referred to as Voltage, or node, Sampling.

→ The output current is sampled by connecting the feedback network in series with the output as shown in figure (b).
This type of connection is referred to as current, or loop, Sampling.

Feedback Network:

→ It may consists of resistors, capacitors and inductors. Most often it is simply a resistive configuration.

→ It provides reduced portion of the output as feedback signal to the input mixer network.

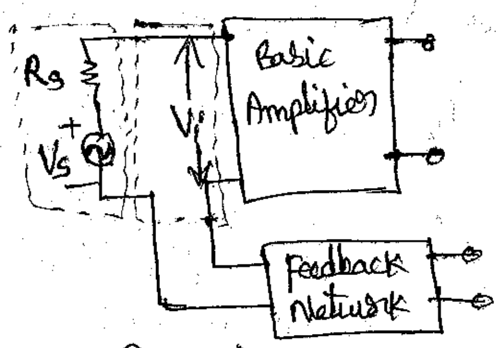
It is given as, $V_f = \beta V_o$

where 'β' is a feedback factor or feedback ratio and lies between 0 and 1.

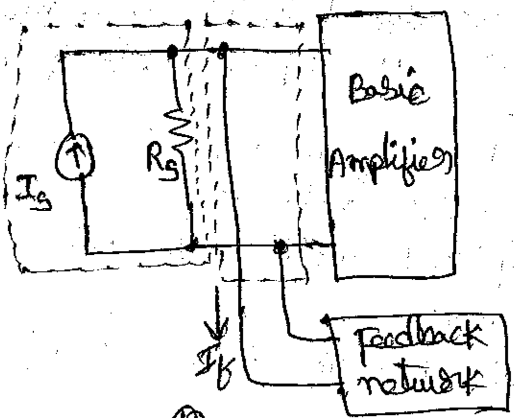
Mixer Network:

→ Like Sampling there are two ways of mixing feedback signal with the input signal.

→ These are series input connection and shunt input connection.



(a) Series mixing



(b) shunt mixing

→ There are two types of feedback
(i) positive feedback
(ii) Negative feedback

Positive feedback:

→ If the feedback signal 'V_f' is in phase with input signal V_s, then the net effect of the feedback will increase the input signal given to the amplifier, i.e $V_i = V_s + V_f$.

→ Hence, the input voltage applied to the basic amplifier is increased thereby increasing V_o exponentially.

→ This type of feedback is said to be positive or regenerative feedback.

→ Gain of the amplifier with positive feedback is,

$$A_f = \frac{V_o}{V_s} = \frac{V_o}{V_i - V_f}$$

$$A_f = \frac{V_o/V_i}{1-(V_f/V_i)} = \frac{V_o/V_i}{1-\frac{V_f}{V_o}\cdot\frac{V_o}{V_i}} = \frac{A}{1-\beta\cdot A} \quad \left\{\because \beta = \frac{V_f}{V_i}\right\}$$

$$\therefore A_f = \frac{A}{1-A\beta}$$

→ Here, $|A_f| > |A|$. The product of the open loop gain and the feedback factor is called the loop gain, i.e loop gain $= A\beta$.

→ If $|A\beta| = 1$, then $A_f = \infty$. Hence, the gain of the amplifier with positive feedback is infinite and the amplifier gives an a.c output without a.c input signal. Thus the amplifier acts as an oscillator.

→ The positive feedback increases the instability of an amplifier, reduces the bandwidth and increases the distortion and noise.

→ The property of the positive feedback is utilized in oscillators.

Negative feedback:

→ If the feedback signal V_f is out of phase with the input signal V_s, then $V_i = V_s - V_f$

→ So the input voltage applied to the basic amplifier is decreased and correspondingly the output is decreased.

→ Hence the voltage gain is reduced. This type of feedback is known as negative or degenerative feedback.

→ Gain of the amplifier with negative feedback is,

$$A_f = \frac{V_o}{V_s} = \frac{V_o}{V_i + V_f} = \frac{(V_o/V_i)}{1+(V_f/V_i)} = \frac{(V_o/V_i)}{1+\frac{V_f}{V_o}\cdot\frac{V_o}{V_i}} = \frac{A}{1+A\beta}$$

→ Here, $|A_f| < |A|$. If $|A\beta| \gg 1$, then $A_f \approx 1/\beta$, where β is a feedback ratio. Here, the gain depends less on the operating potentials and the characteristics of the transistor or vaccum tube.

→ The gain may be made to depend entirely on the feedback network. If the feedback network contains only stable passive elements, the gain of the amplifier using negative feedback is also stable.

→ The stabilization of the d.c operating point of a transistor amplifier is accomplished b the use of negative feedback as far as the d.c potential is concerned and the operating is kept constant in the case of change in temperature or a change in the h_{fe} or β of a transistor.

→ Negative feedback always helps to increase the bandwidth, decrease distortion an noise, modify input and output resistances as desired.

→ All the above advantages are obtained at the expense of reduction in voltage gain.

General characteristics of Negative feedback Amplifiers:

1) Stabilization of Gain:

The gain of the amplifier with negative feedback is $A_f = \frac{A}{1+A\beta}$

Differentiating both the sides with respect to A we get,

$$\frac{dA_f}{dA} = \frac{(1+\beta A)\cdot 1 - \beta A}{(1+\beta A)^2} = \frac{1}{(1+\beta A)^2}$$

$$\Rightarrow dA_f = \frac{dA}{(1+\beta A)^2}$$

Dividing both sides by A_f we get,

$$\frac{dA_f}{A_f} = \frac{dA}{(1+\beta A)^2}\cdot\frac{1}{A_f}$$

$$= \frac{dA}{(1+\beta A)^2}\cdot\frac{(1+\beta A)}{A} \qquad \text{since } A_f = \frac{A}{1+\beta A}$$

$$\frac{dA_f}{A_f} = \frac{dA}{A}\cdot\frac{1}{(1+\beta A)}$$

where $\frac{dA_f}{A_f}$ = Fractional change in amplification with feedback

$\frac{dA}{A}$ = Fractional change in amplification without feedback

The term $\left(\frac{1}{1+A\beta}\right)$ is called sensitivity.

→ Therefore, the sensitivity is defined as the ratio of percentage change in voltage gain with feedback to the percentage change in voltage gain without feedback.

$$\text{Sensitivity} = \frac{(dA_f/A_f)}{(dA/A)} = \frac{1}{1+A\beta}$$

→ The reciprocal of the term sensitivity is called desensitivity i.e

$$\text{Desensitivity} = (1+A\beta) = D$$

(2)

Increase of Bandwidth (Cut-off frequencies):

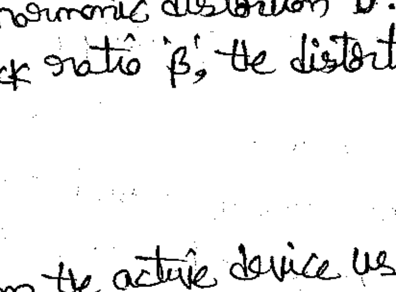
→ The bandwidth of an amplifier is the difference between the upper cut-off frequency 'f_H' and the lower cut-off frequency 'f_L'.

→ The product of voltage gain and bandwidth of an amplifier without feedback and with feedback remains the same i.e $A_f \times BW_f = A \times BW$.

→ As the voltage gain of a feedback amplifier reduces by the factor $1/(1+A\beta)$, its bandwidth would be increased by $(1+A\beta)$ i.e $BW_f = BW(1+A\beta)$, where 'A' is the midband gain without feedback.

→ Due to the negative feedback in the amplifier, the upper cut-off frequency 'f_H' is increased by the factor $(1+A\beta)$ and the lower cut-off frequency 'f_L' is decreased by the same factor $(1+A\beta)$. These upper and lower 3dB frequencies of an amplifier with negative feedback are given by the relations,

$$f_{Hf} = f_H(1+A\beta) \quad \text{and} \quad f_{Lf} = \frac{f_L}{1+A\beta}$$



(3)

Decreased Distortion:

→ Consider an amplifier with an open loop voltage gain and a total harmonic distortion 'D'. Then, with the introduction of negative feedback with the feedback ratio 'β', the distortion will reduce to,

$$D_f = \frac{D}{1+A\beta}$$

(4)

Decreased Noise:

→ There are many sources of noise in an amplifier depending upon the active device used. The noise N, can be reduced by a factor of [1/(1+Aβ)] in a similar manner to non-linear distortion with using the negative feedback with the feedback ratio 'β'.

Thus the noise with feedback is given by,

$$N_f = \frac{N}{1+A\beta}$$

(5) Increase in input impedance : ✗

→ An amplifier should have high input impedance (resistance) so that it will not load the preceding stage or the input voltage source. Such a desirable characteristic can be achieved with the help of negative series ~~voltage~~ feedback.

The input impedance with feedback is given by,

$$Z_{if} = Z_i (1+A\beta)$$

Thus the input impedance is increased by a factor of $(1+A\beta)$.

(6) Decrease in output impedance : ✗

→ An amplifier with low output impedance (resistance) is capable of delivering power (or voltage) to the load without much loss. Such a desirable characteristics is achieved by employing negative ~~series~~ voltage feedback in an amplifier.

The output impedance with feedback is expressed by,

$$Z_{of} = \frac{Z_o}{1+A\beta}$$

Here the output impedance is reduced by a factor $(1+A\beta)$.

problem: ✓

An amplifier has mid-band voltage gain A_V of 1000 with $f_L = 50\,Hz$ and $f_H = 50\,kHz$. If 5% feedback is applied then calculate A_{Vf}, f_{Lf} and f_{Hf} with feedback.

Solⁿ: $A_V = 1000$, $f_L = 50\,Hz$, $f_H = 50\,kHz$, $\beta = \frac{5}{100} = 0.05$

$$A_{Vf} = \frac{A_V}{1+A_V\beta} = \frac{1000}{1+1000\times 0.05} = 19.6$$

$$f_{Lf} = \frac{f_L}{1+\beta A_V} = \frac{50}{1+0.05\times 1000} = 0.98\ Hz$$

$$f_{Hf} = f_H(1+\beta A_V) = 2.55\ MHz.$$

problem: ✗ ✗

An amplifier with open loop voltage gain of 1000 delivers 10W of power output at 10% second harmonic distortion when input is 10mV. If 40dB negative feedback is applied and output power is to remain at 10W, determine required input signal V_s and second harmonic distortion with feedback.

Solⁿ: $A_V = 1000$

problem: An amplifier with open loop gain of $A = 2000 \pm 150$ is available. It is necessary to have the amplifier whose voltage gain varies by not more than $\pm 0.2\%$ with feedback. Calculate β and A_f.

Solⁿ:

$$\frac{dA_f}{A_f} = \frac{1}{1+\beta A}\cdot\frac{dA}{A} \Rightarrow \frac{0.2}{100} = \frac{1}{1+\beta A}\cdot\frac{150}{2000}$$

$$\Rightarrow 1+\beta A = 37.5$$

$$\Rightarrow \beta \times 2000 = 36.5$$

$$\Rightarrow \beta = 0.01825$$

$$\therefore A_f = \frac{A}{1+\beta A} = \frac{2000}{1+0.01825\times 2000} = 53.33.$$

problem: If an amplifier has a bandwidth of 300 KHz and voltage gain of 100, what will be the new bandwidth and gain if 10% negative feedback is introduced? what will be the gain bandwidth product before and after feedback? what should be the amount of feedback if the bandwidth is to be limited to 800 KHz.

Solⁿ: $BW = 300\,KHz$, $A = 100$, $\beta = \frac{10}{100} = 0.1$

$$BW_f = (1+\beta A)\cdot BW = (1+0.1\times 100)\times 300\times 10^3 = 3.3\,MHz.$$

Gain bandwidth product before feedback $= A\cdot BW = 100\times 300K = 30\,MHz.$

$$A_f = \frac{A}{1+A\beta} = \frac{100}{1+100\times 0.1} = 9.09$$

Gain bandwidth product after feedback $= A_f \cdot BW_f = 9.09\times 3.3M = 30\,MHz.$

If bandwidth is to be limited to 800 KHz we have,

$$BW_f = (1+A\beta)\cdot BW$$

$$\Rightarrow 800\times 10^3 = (1+100\times\beta)\times 300\times 10^3$$

$$\Rightarrow \beta = 0.01667$$

problem: An amplifier has a voltage gain of 4000. Its input impedance is 2K and output impedance is 60K. Calculate the voltage gain, input and output impedance of the circuit if 5% of the feedback is fed in the form ~~series voltage~~ negative f

Soln: $A_V = 4000$, $Z_i = 2K$, $Z_o = 60K$, $\beta = \frac{5}{100} = 0.05$

$$\therefore A_{Vf} = \frac{A_V}{1+\beta A_V} = \frac{4000}{1+0.05\times 4000} = 19.9$$

$$Z_{if} = Z_i\,(1+\beta A_V) = 2\times10^3\,(1+0.05\times4000) = 402\ K\Omega$$

$$Z_{of} = \frac{Z_o}{1+\beta A_V} = \frac{60\times10^3}{1+0.05\times4000} = 298.5\ \Omega$$

problem: An amplifier with negative feedback has a voltage gain of 120. It is found that without feedback an input signal of 60mV is required to produce a particular output, whereas with feedback the input signal must be 0.5V to get the same output. Find A_V and β of the amplifier.

Soln: $A_{Vf} = 120$, $V_i = 60mV$, $V_s = 0.5V$

$$A_V = \frac{V_o}{V_i} = \frac{V_o}{60\times10^{-3}}$$

$$A_{Vf} = \frac{V_o}{V_s} = \frac{V_o}{0.5}$$

$$\Rightarrow 120 = \frac{V_o}{0.5} \Rightarrow V_o = 60V.$$

$$\therefore A_V = \frac{60}{60\times10^{-3}} = 1000$$

$$A_{Vf} = \frac{A_V}{1+\beta A_V} \Rightarrow 120 = \frac{1000}{1+\beta\times1000} \Rightarrow \beta = 0.00733$$

Advantages of Negative feedback amplifier:

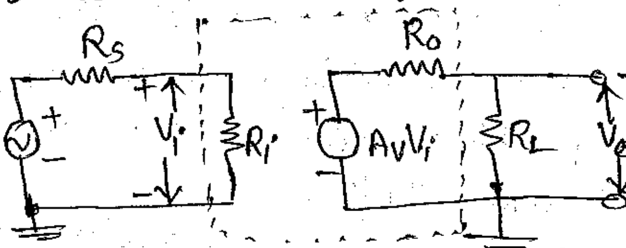
1) Gain is stabilized
2) Frequency, phase distortion is decreased.
3) Bandwidth is increased
4) Effect of noise decreases as gain is decreased.
5) R_{if} and R_{of} are increased or decreased inorder to meet the requirements of amplifiers according to feedback arrangement.

→ All the above advantages are at the cost of only one drawback of reduction in gain.

UNIT-VII FEEDBACK AMPLIFIERS.

Classification of amplifiers :

→ Amplifiers Can be classified based on the magnitudes of the input and out impedan into four broad Categories as,
(i) Voltage amplifier (ii) Current amplifier (iii) transconductance amplifier and (iv) transresistance amplifier.



$(R_i \to \infty)$ $R_i >> R_S$ and $R_L >> R_o$ (or) $(R_o \to$

Fig: Thevenin's equivalent CKt of Voltage amplifier.

Voltage amplifier :

→ If the amplifier input resistance R_i is large Compared with the Source resistance R_S i.e $R_i >> R_S$ then $V_i \approx V_S$.

→ If the external load resistance R_L is large Compared with the output resistance R_o of the amplifier i.e $R_L >> R_o$ then $V_o \approx A_V V_i \approx A_V V_S$

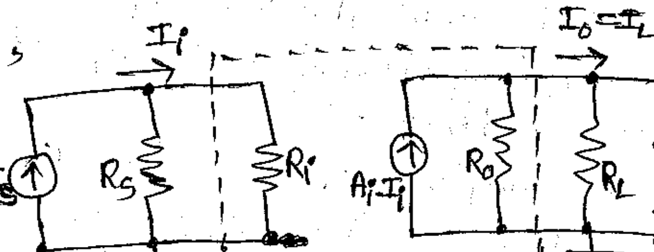
therefore $A_V = \frac{V_o}{V_S}$.

∴ This type of amplifier provides a Voltage output proportional to the Voltage input and the proportionality factor does not depend on the magnitudes of the Source and load resistances.

→ Hence this amplifier is Called Voltage amplifier.

∴ An ideal Voltage amplifier must have infinite input resistance R_i and zero output resistance R_o.

→ For practical Voltage amplifier we must have,
$R_i >> R_S$ and $R_L >> R_o$.



$R_i << R_S$ and $R_L << R_o$
$(R_i \to 0)$ $(R_o \to \infty)$

Fig: Norton's equivalent circuit of Current amplifier.

Current Amplifier :

→ If the amplifier input resistance R_i is ~~large~~ Small Compared with the Source resistance R_S i.e $R_i << R_S$ then $I_i \approx I_S$.

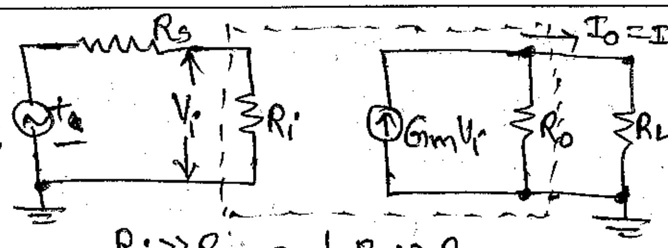
→ If the external load resistance R_L is Small Compared with the output resistance R_o i.e $R_L << R_o$ then $I_L \approx A_i I_i \approx A_i I_S \Rightarrow A_i \approx \frac{I_L}{I_S}$.

∴ This type of amplifier provides an ~~voltage~~ current output proportional to the ~~voltage~~ input current and the proportionality factor does not depend on the magnitudes of the Source and load resistances.

→ Hence this amplifier is Called ~~voltage~~ Current amplifier.

∴ An ideal ~~voltage~~ Current amplifier must have zero input resistance and infinite output resistance. For practical Current amplifier we must have $R_i << R_S$ and $R_L <<$

Transconductance amplifier:



$R_i >> R_s$ and $R_o >> R_L$

→ If the amplifier input resistance R_i is large compared to the external source resistance R_s i.e $R_i >> R_s$ then $V_i \approx V_s$.

→ If the external load resistance R_L is small when compared to the output resistance R_o of the amplifier i.e $R_o >> R_L$ then $I_L \approx G_m V_i \approx G_m V_s$

$\Rightarrow G_m = I_L / V_s$.

→ This type of amplifier supplies an output current which is proportional to the signal or input voltage independent of the magnitudes of R_s and R_L.

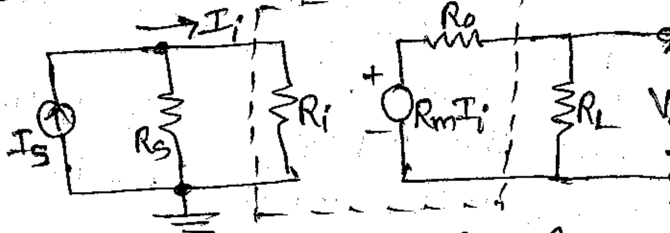
→ Hence this amplifier is called transconductance amplifier.

→ Ideally this type of amplifier must have infinite input resistance R_i and infinite output resistance R_o.

→ For practical transconductance amplifier we must have $R_i >> R_s$ and $R_o >> R_L$.

→ A transconductance amplifier is represented by a Thevenin's equivalent in its input circuit and Norton's equivalent in its output circuit as shown in above figure.

Transresistance amplifier:



$R_i << R_s$ $R_o << R_L$

→ A transresistance amplifier is represented by a Norton's equivalent in its input circuit and a Thevenin's equivalent in its output circuit as shown in figure.

→ If the amplifier input resistance R_i is small compared to the source resistance R_s i.e $R_i << R_s$ then $I_i \approx I_s$.

→ If the external load resistance R_L is large when compared to the output resistance R_o of the amplifier i.e $R_L >> R_o$ then $V_o \approx R_m I_i \approx R_m I_s$ $\Rightarrow$ $R_m = \frac{V_o}{I_s}$.

→ This type of amplifier provides voltage output which is proportional to the input or source current independent of the magnitudes of R_s and R_L.

→ Hence this amplifier is called transresistance amplifier.

→ Ideally this type of amplifier must have zero input resistance and zero output resistance.

→ For practical transresistance amplifier we must have $R_i << R_s$ and $R_o << R_L$

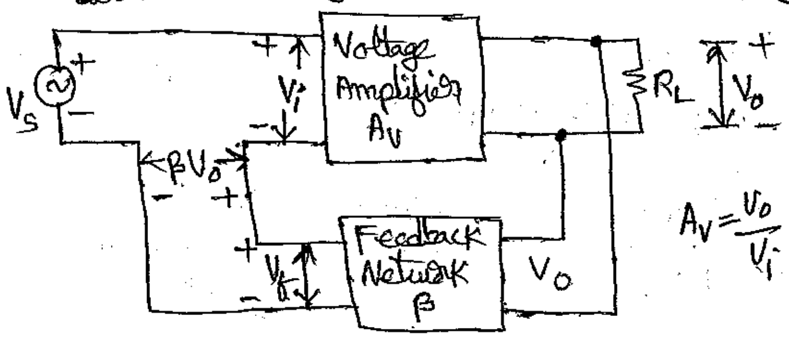
Classification of Feedback Amplifiers:

→ Based on the topology of connections, the feedback amplifiers are classified into four configurations,

1) Voltage series feedback
2) Current series feedback
3) Current shunt feedback
4) Voltage shunt feedback.

① Voltage amplifier with Voltage series feedback.

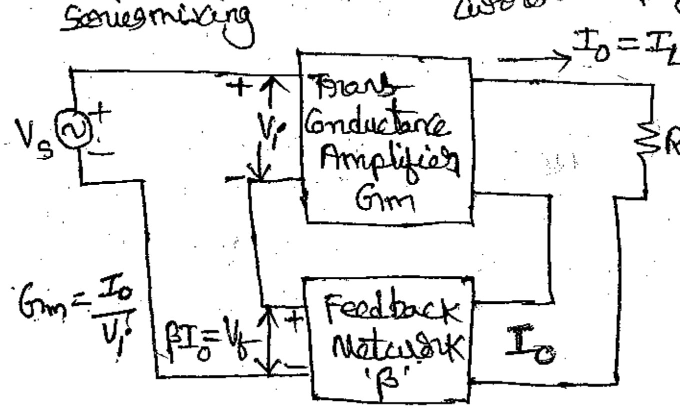
series mixing — Voltage sampling



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

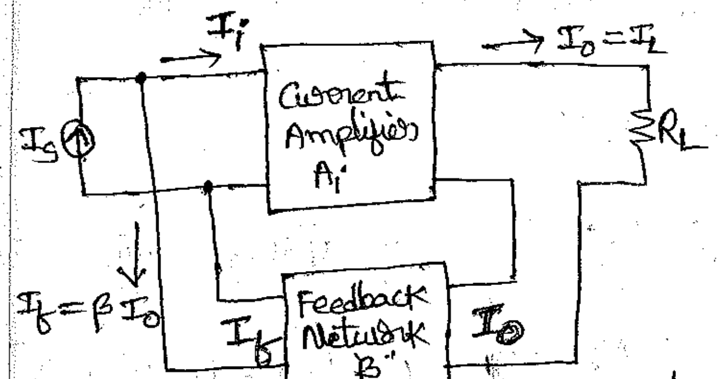
② Transconductance amplifier with Current series feedback.

series mixing — current sampling



$G_m = \frac{I_o}{V_i}$

③ Current amplifier with Current shunt feedback

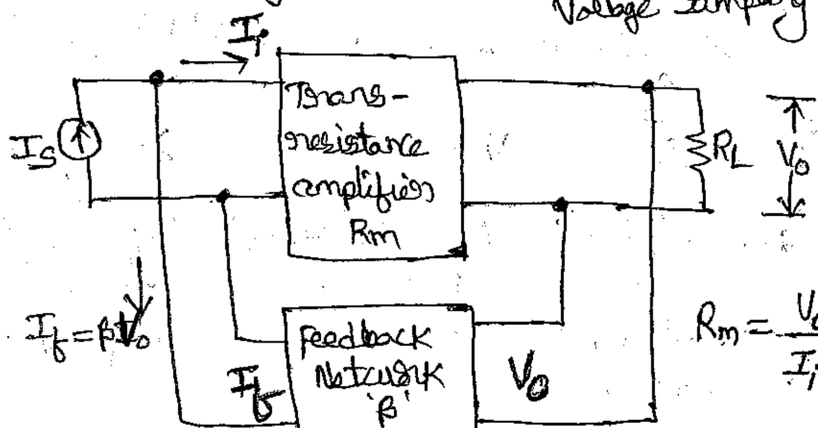


shunt mixing — Current Sampling

$A_I = \frac{I_o}{I_i}$

④ Transresistance amplifier with Voltage shunt feedback

shunt mixing — Voltage Sampling



$R_m = \frac{V_o}{I_i}$

Effect of Negative feedback upon output and Input resistances:

① output resistance:

→ Negative feedback which samples the output Voltage (i.e Voltage sampling) regardless of how this output signal is returned to the input, tends to decrease the output resistance.

→ For example ① if R_L increases so that V_o increases, the effect of feeding this Voltage back to the input in a degenerative manner (negative feedback) is to cause V_o to increase less than it would if there were no feedback. Hence the output Voltage tends to remain constant as R_L changes, which means that $R_{of} << R_L$. Thus this type of feedback i.e sampling the output Voltage reduces the output resistance.

→ Similarly, negative feedback which samples the output current (i.e current sampling) will tend to hold this current constant. Hence an output current source is created ($R_{of} >> R_L$) and we conclude that this type of sampling connection increases the output resistance.

② Input resistance:

→ If the feedback signal is returned to the input in series (i.e series mixing) to oppose the applied voltage, regardless of whether it is obtained by sampling the output voltage or current, it tends to increase the input resistance.

→ Since the feedback voltage V_f opposes V_s, the current I_s is less than it would be if V_f were absent. Hence $R_{if} \equiv \frac{V_S}{I_S} - R_S$ is increased.

→ Negative feedback in which the output signal is fedback to the input in parallel (shunt mixing) tends to decrease the input resistance.

→ The current drawn I_s from the signal source is increased over what it would be if there were no feedback current I_f. Hence R_{if} is decreased because of this type of feedback.

Summary:

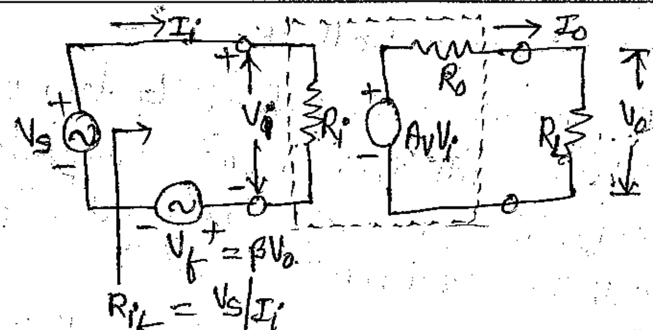
→ Voltage sampling reduces output resistance and current sampling increases output resistance and shunt mixing decreases input resistance.

→ Series mixing increases input resistance.

Effects of Negative feedback on Amplifier characteristics:

Parameter	Voltage-Series	Current-Series	Current-Shunt	Voltage Shunt
Gain with f/b	$A_{Vf} = A_V/(1+\beta A_V)$ Decreases	$G_{mf} = G_m/(1+\beta G_m)$ Decreases	$A_{if} = A_i/(1+\beta A_i)$ Decreases	$R_{mf} = R_m/(1+\beta R_m)$ Decreases
Stability and Frequency response	Improves	Improves	Improves	Improves
Frequency distortion, Noise and Non-linear distortion	Reduces	Reduces	Reduces	Reduces
Input resistance	$R_{if} = R_i(1+\beta A_V)$ Increases	$R_{if} = R_i(1+\beta G_M)$ Increases	$R_{if} = R_i/(1+\beta A_i)$ Decreases	$R_{if} = R_i/(1+\beta R_M)$ Decreases
Output resistance	$R_{of} = R_o/(1+\beta A_V)$ Decreases	$R_{of} = R_o(1+\beta G_M)$ Increases	$R_{of} = R_o(1+\beta A_i)$ Increases	$R_{of} = R_o/(1+\beta R_M)$ Decreases
Bandwidth	Increases	Increases	Increases	Increases.

Voltage series Feedback:



The input resistance with feedback is given as,

$$R_{if} = \frac{V_s}{I_i}$$

Applying KVL to the input side we get,

$$V_s - I_i R_i - V_f = 0 \Rightarrow V_s = I_i R_i + V_f$$

$$V_s = I_i R_i + \beta V_o$$

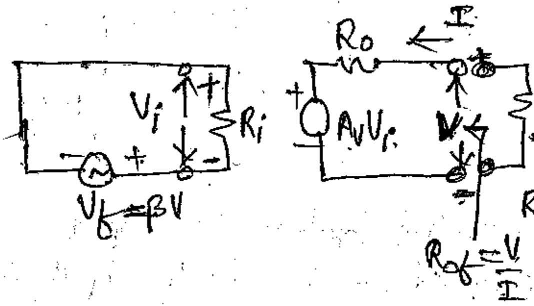
But, $V_o = A_V \cdot V_i \cdot \frac{R_L}{R_o + R_L} = A_V' \cdot I_i R_i$ $\left\{ \because V_i = I_i R_i \text{ \& } A_V' = \frac{A_V \cdot R_L}{R_o + R_L} \right\}$

A_V represents the open circuit voltage gain without feedback and A_V' is the voltage gain without feedback taking the load R_L into account.

$$\therefore V_s = I_i R_i + \beta V_o = I_i R_i + \beta A_V' \cdot I_i R_i = I_i R_i (1 + \beta A_V')$$

$$\Rightarrow \boxed{R_{if} = \frac{V_s}{I_i} = R_i (1 + \beta A_V')}$$

→ The output resistance can be measured by shorting the input source $V_s = 0$ and looking into the output terminals with R_L disconnected.



Applying KVL to the output side we get,

$$A_V V_i + I R_o - V = 0 \Rightarrow I = \frac{V - A_V V_i}{R_o}$$

The input voltage is given as,

$$V_i = -V_f = -\beta V \quad \{\because V_s = 0\}$$

$$\therefore I = \frac{V + A_V \cdot \beta V}{R_o} = \frac{V(1 + \beta A_V)}{R_o} \Rightarrow \boxed{R_{of} = \frac{V}{I} = \frac{R_o}{1 + \beta A_V}}$$

Here R_{of} is the output resistance with feedback without taking R_L into account.

R_{of}' is the output resistance with feedback taking R_L into account.

$$\therefore R_{of}' = R_{of} \| R_L = \frac{R_o'}{1 + \beta A_V'} \quad \text{where } R_o' = \frac{R_o R_L}{R_o + R_L} \text{ and } A_V' = \frac{A_V R_L}{R_o + R_L}$$

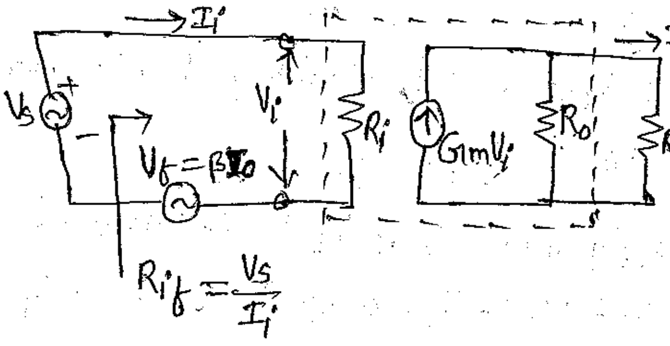
where A_V' is the open loop voltage gain taking R_L into account.

→ Voltage gain with feedback is $A_{Vf} = \frac{A_V}{1 + \beta A_V}$.

→ Current gain with feedback A_{If} remains unchanged.

Current Series Feedback:

The current series feedback topology is as shown in figure with input circuit represented by Thevenin's equivalent circuit and output circuit by Norton's equivalent circuit.



The input resistance with feedback is given as,

$$R_{if} = \frac{V_s}{I_i}$$

Applying KVL to the input side we get,

$$V_s - I_i R_i - V_f = 0 \Rightarrow V_s = I_i R_i + V_f = I_i R_i + \beta I_o$$

But output current is $I_o = G_m \cdot V_i \cdot \frac{R_o}{R_o + R_L} = G_M \cdot V_i$ where $G_M = \frac{G_m R_o}{R_o + R_L}$

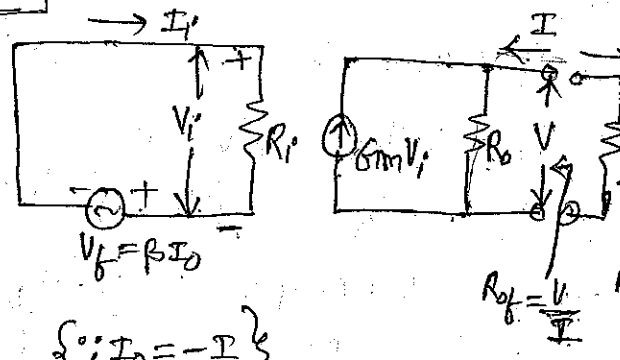
where G_m represents the open circuit transconductance without feedback and G_M is the transconductance without feedback taking the load R_L into account.

Substituting value of I_o we get,

$$V_s = I_i R_i + \beta I_o = I_i R_i + \beta G_M V_i = I_i R_i + \beta G_M I_i R_i = I_i R_i (1 + \beta G_M)$$

$$\rightarrow \boxed{R_{if} = \frac{V_s}{I_i} = R_i (1 + \beta G_M)}$$

→ In this topology the output resistance can be measured by shorting the input source $V_s = 0$ and looking into the output terminals with R_L disconnected.



Applying KCL to the output node we get,

$$I = \frac{V}{R_o} - G_m V_i$$

The input voltage is given as, $V_i = -V_f = -\beta I_o = \beta I$ $\{\because I_o = -I\}$

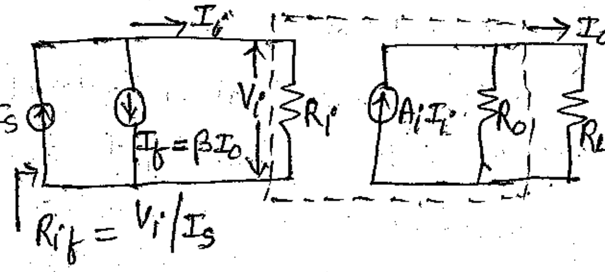
$$\therefore I = \frac{V}{R_o} - G_m \cdot \beta I \Rightarrow \frac{V}{R_o} = I(1 + \beta G_m) \Rightarrow \boxed{R_{of} = \frac{V}{I} = R_o(1 + \beta G_m)}$$

$$R'_{of} = R_{of} || R_L = \frac{R'_o (1 + \beta G_m)}{(1 + \beta G_M)}$$ where $R'_o = \frac{R_o R_L}{R_o + R_L}$ and $G_M = \frac{G_m R_o}{R_o + R_L}$

→ Voltage gain with feedback $A_{vf} = \frac{A_V}{1 + \beta A_V}$.

→ Current gain with feedback A_{If} remains unchanged.

Current shunt Feedback:



→ The Current shunt feedback topology is as shown in figure with amplifier input and output circuit replaced by Norton's equivalent circuit.

Applying KCL to the input node we get,

$I_s = I_i + I_f = I_i + \beta I_o$

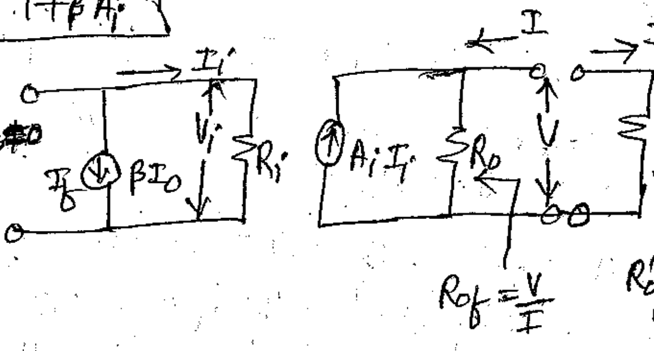
The output current I_o is given as, $I_o = A_i I_i \cdot \frac{R_o}{R_o+R_L} = A_i' \cdot I_i$ where $A_i' = \frac{A_i R_o}{R_o+R_L}$

A_i represents open circuit current gain without feedback and A_i' is the current gain without feedback taking load R_L into account.

$\therefore\ I_s = I_i + \beta I_o = I_i + \beta A_i' I_i = I_i(1+\beta A_i')$

$\therefore$ Input resistance with feedback is,

$$R_{if} = \frac{V_i}{I_s} = \frac{V_i}{I_i(1+\beta A_i')} \Rightarrow \boxed{R_{if} = \frac{R_i}{1+\beta A_i'}}$$



→ In this topology, the output resistance can be measured by open circuiting the input source $I_s = 0$ and looking into the output terminals with R_L disconnected.

Applying KCL to the output node we get,

$$I = \frac{V}{R_o} - A_i I_i$$

The input current is given as, $I_i = -I_f = -\beta I_o$ $\{\because I_s = 0\}$

$I_i = \beta I$ $\{\because I = -I_o\}$

$$\therefore\ I = \frac{V}{R_o} - A_i \beta I \Rightarrow I(1+\beta A_i) = \frac{V}{R_o}$$

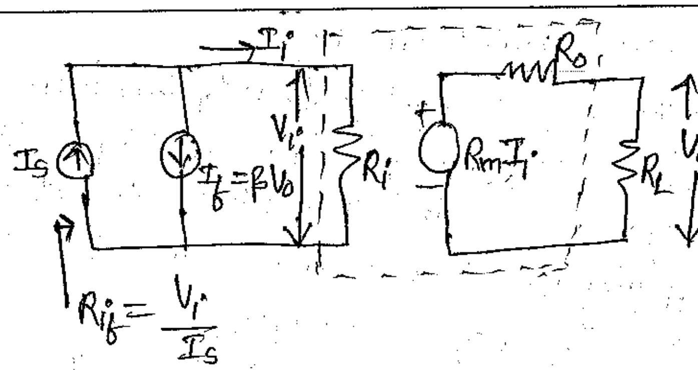
$$\therefore \boxed{R_{of} = \frac{V}{I} = R_o(1+\beta A_i)}$$

$$R_{of}' = R_{of} \| R_L = \frac{R_o'(1+\beta A_i)}{(1+\beta A_i')}$$ where $R_o' = \frac{R_o R_L}{R_o+R_L}$ and $A_i' = \frac{A_i R_o}{R_o+R_L}$

→ Current gain with feedback $A_{if} = \frac{A_i}{1+\beta A_i}$

→ Voltage gain with feedback A_{vf} remains unchanged.

Voltage shunt Feedback :



→ The Voltage shunt feedback topology is as shown in figure with amplifier's input circuit is represented by Norton's equivalent circuit and output circuit represented by Thevenin's equivalent.

Applying KCL at input node we get,

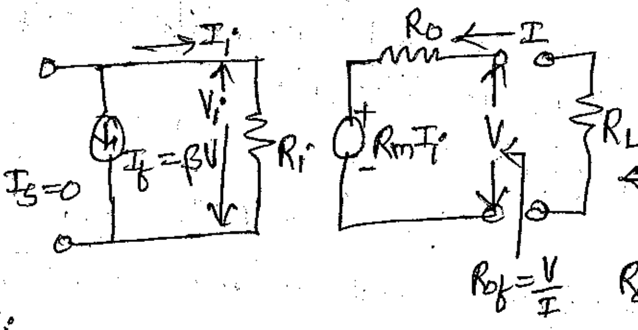
$$I_S = I_i + I_f = I_i + \beta V_o$$

But, $V_o = R_m I_i \cdot \dfrac{R_L}{R_o + R_L} = R_M \cdot I_i$ where $R_M = \dfrac{R_m R_L}{R_o + R_L}$

where R_m represents the open circuit transresistance without feedback and R_M is the transresistance without feedback taking load R_L into account.

$$\therefore I_S = I_i + \beta R_M I_i = I_i (1 + \beta R_M)$$

$\therefore$ Input resistance with feedback $R_{if} = \dfrac{V_i}{I_S} = \dfrac{V_i}{I_i(1+\beta R_M)} = \dfrac{R_i}{1+\beta R_M}$ $\{\because R_i = V_i / I_i\}$



In this topology, the output resistance can be measured by shorting the input source $V_s = 0$ and looking into the output terminals with R_L disconnected.

Applying KVL to the output side we get,

$$R_m I_i + I R_o - V = 0 \Rightarrow I = \frac{V - R_m I_i}{R_o}$$

The input current is given as, $I_i = -I_f = -\beta V$.

$$\therefore I = \frac{V + R_m \beta V}{R_o} = \frac{V(1+\beta R_m)}{R_o} \Rightarrow \boxed{R_{of} = \frac{V}{I} = \frac{R_o}{1+\beta R_m}}$$

$$R'_{of} = R_{of} \| R_L = \frac{R'_o}{1+\beta R_M} \quad \text{where } R'_o = \frac{R_o R_L}{R_o + R_L} \text{ and } R_M = \frac{R_m R_L}{R_o + R_L}$$

→ Current gain with feedback $A_{if} = \dfrac{A_i}{1+\beta A_i}$

→ Voltage gain with feedback remains unchanged.

Method of Feedback Amplifier ~~Amplifier~~ Analysis:

For analysing the feedback amplifier, it is necessary to go through the following steps,

Step 1: Identity Topology (Type of feedback)

(a) To find the type of sampling network

(i) By shorting the output i.e $V_o = 0$ if feedback signal becomes zero, then it is called Voltage Sampling

(ii) By opening the output loop i.e $I_o = 0$ if feedback signal becomes zero then it is called Current Sampling.

(b) To find the type of mixing network

(i) If the feedback signal is subtracted from the externally applied signal as a Voltage in the input loop, it is called series mixing.

(ii) If the feedback signal is subtracted from the externally applied signal as a current in the input loop, it is called shunt mixing.

Thus by finding the type of sampling network and mixing network, type of feedback amplifier can be determined.

Step 2: To find the input circuit

(i) For Voltage sampling, the output Voltage is made zero by shorting the output.

(ii) For Current sampling, the output current is made zero by opening the output loop.

Step 3: To find the output circuit

(i) For series mixing, the input current is made zero by opening the input loop.

(ii) For shunt mixing, the input Voltage is made zero by shorting the input

In step 2 and step 3 ensure that the feedback is reduced to zero without altering the loading on the basic amplifier.

step 4 (optional): Replace each active device by its h-parameter model at low frequency.

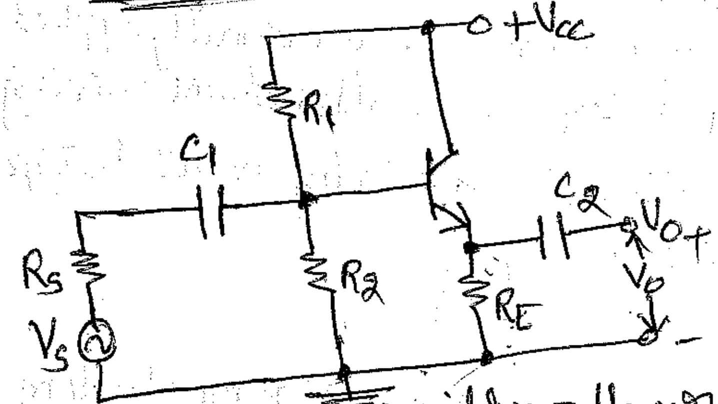
step 5: Find open loop gain 'A' (gain without feedback) of the amplifier.

step 6: Indicate X_f (feedback voltage or feedback current) and X_o (output voltage or output current) on the circuit and evaluate $\beta = X_f / X_o$.

step 7: From A and β find D, A_f, R_{if}, R_{of} and R'_{of}.

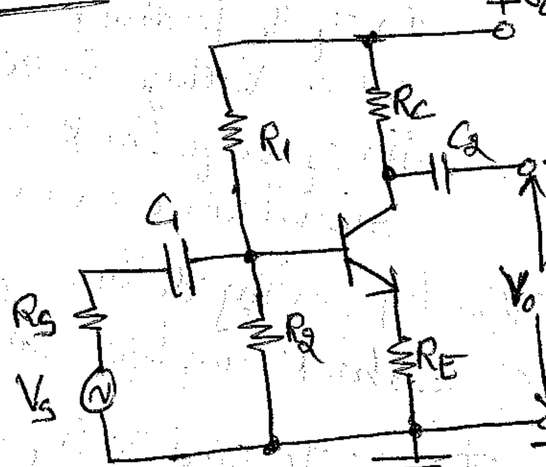
Practical Feedback amplifier circuits:

① Voltage Series Feedback



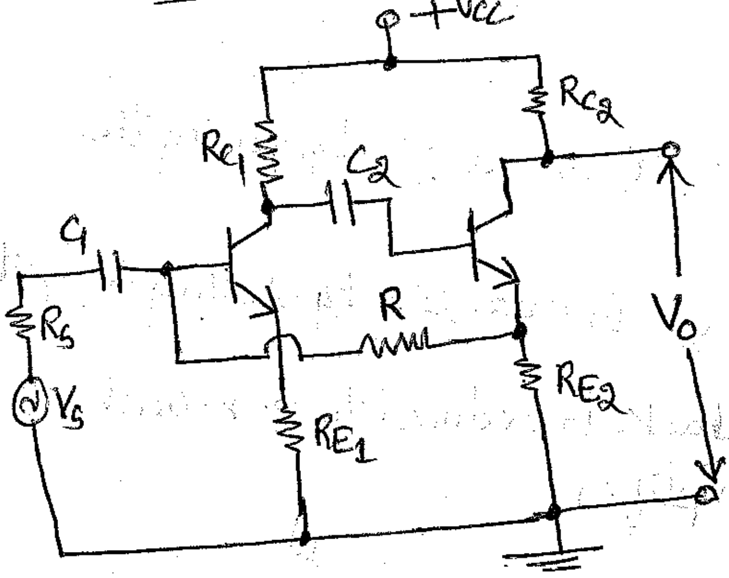
Fig①: CC Amplifier (or) Emitter Follower

② Current Series Feedback



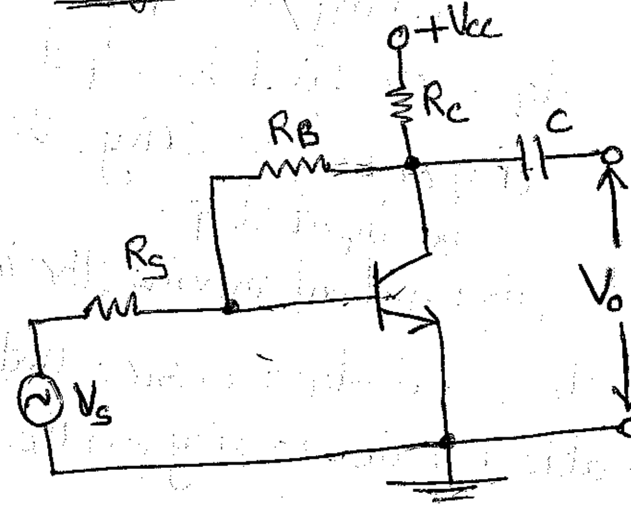
Fig②: CE Amplifier with unbypassed emitter capacitor

③ Current shunt feedback



Fig③:

④ Voltage shunt feedback:



Prob ①: Identify topology with justification for the circuit shown in figure ⓐ. Transistors used are identical and have parameters $h_{ie} = 2K\Omega$, $h_{fe} = 50$, $h_{re} = h_{oe} = 0$. Find A_{vf}, R_{if} & R_{of}'.

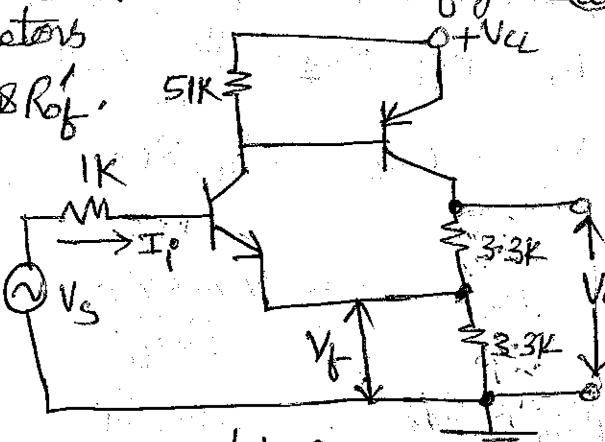


fig ⓐ

Soln:

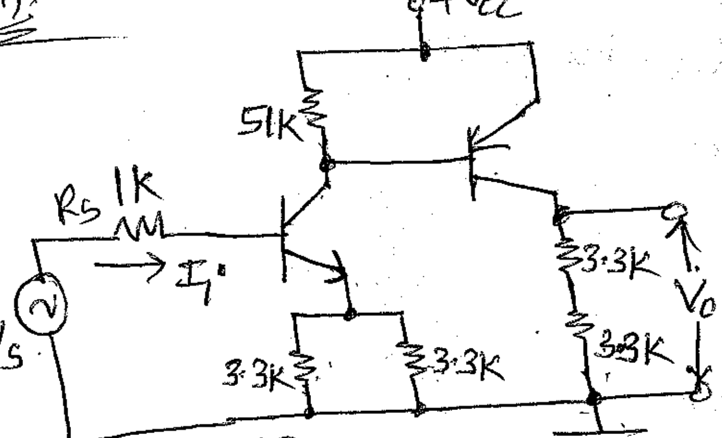


Fig ⓑ

~~step 1: Identify topology~~

By shorting output voltage $V_o = 0$, feedback voltage V_f becomes zero hence it is a voltage sampling. Since feedback is mixed in series with input the topology is voltage series feedback amplifier.

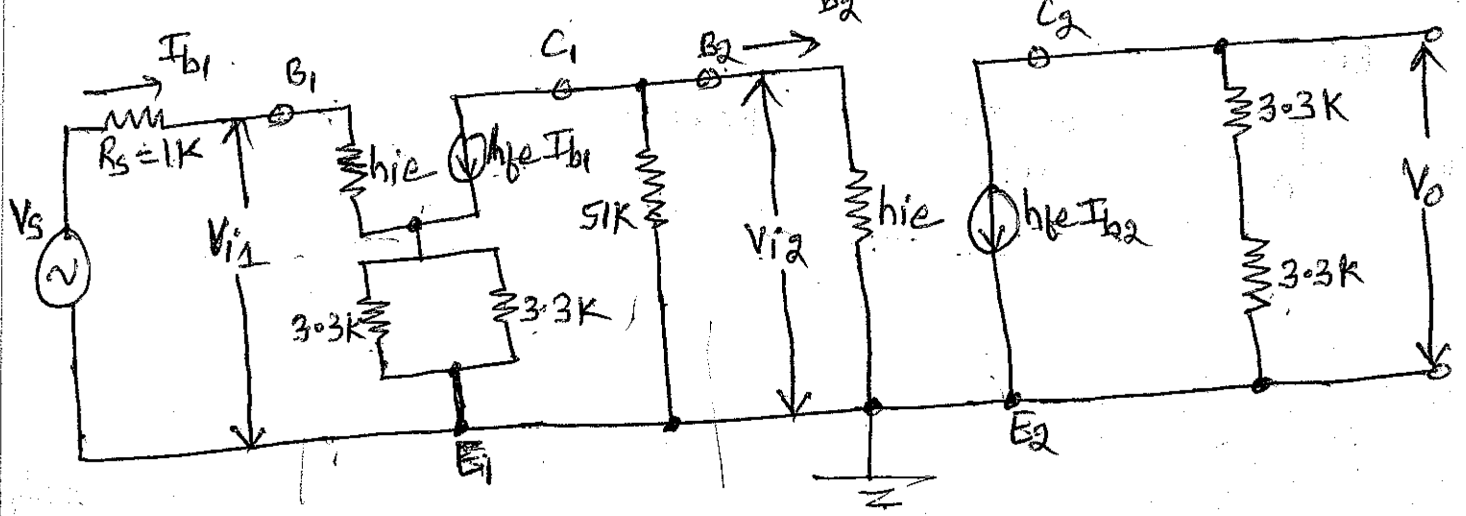
step 2: To find input circuit

To find input circuit set $V_o = 0$. This places the parallel combination of 3.3K and 3.3K at first emitter.

step 3: To find output circuit

To find output circuit set $I_i = 0$. This places resistors 3.3K and 3.3K in series across the output. The resultant circuit is shown in figure ⓑ.

step 4: Replace transistors with their h-parameter equivalent circuits.



Step 5: Find open loop transfer gain

$$\left\{ A_V = A_I \frac{Z_L}{Z_i} \quad \text{But } A_I = -h_{fe} \right\}$$

$$A_V = A_{V2} \cdot A_{V1} = \frac{V_o}{V_{i2}} \times \frac{V_{i2}}{V_{i1}}$$

$$R_{L2} = 3.3K + 3.3K = 6.6K\Omega$$

$$\frac{V_o}{V_{i2}} = A_{V2} = \frac{-h_{fe} R_{L2}}{R_{i2}}$$

$$R_{i2} = h_{ie} = 2K.$$

$$\therefore A_{V2} = \frac{-50 \times 6.6 \times 10^3}{2 \times 10^3} = -165$$

$$A_{V1} = \frac{V_{i2}}{V_{i1}} = \frac{-h_{fe} R_{L1}}{R_{i1}}$$

$$R_{L1} = 51K \| R_{i2} = 51K \| 2K = 1.92K\Omega$$

$$R_{i1} = h_{ie} + (1+h_{fe}) R_E = 2 \times 10^3 + (1+50) \times (3.3K \| 3.3K)$$

$$R_{i1} = 86.15K\Omega$$

$$\therefore A_{V1} = \frac{-50 \times 1.92 \times 10^3}{86.15 \times 10^3} = -1.114$$

$$\therefore A_V = A_{V1} \cdot A_{V2} = (-1.114) \times (-165) = \underline{183.81}$$

$$\beta = \frac{V_f}{V_o} = \frac{3.3K}{3.3K + 3.3K} = 0.5$$

$$D = 1 + A\beta = 1 + 183.8 \times 0.5 = 92.9$$

$$\therefore A_{Vf} = \frac{A_V}{D} = \frac{183.81}{92.9} = 1.98$$

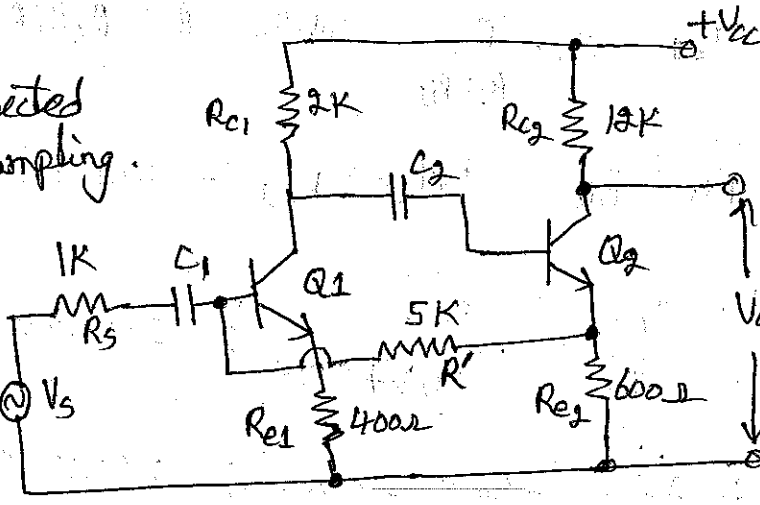
$$R_{if} = R_i D = (R_{i1}) \times D = (86.15 \times 10^3) \times 92.9 = 8.00M\Omega$$

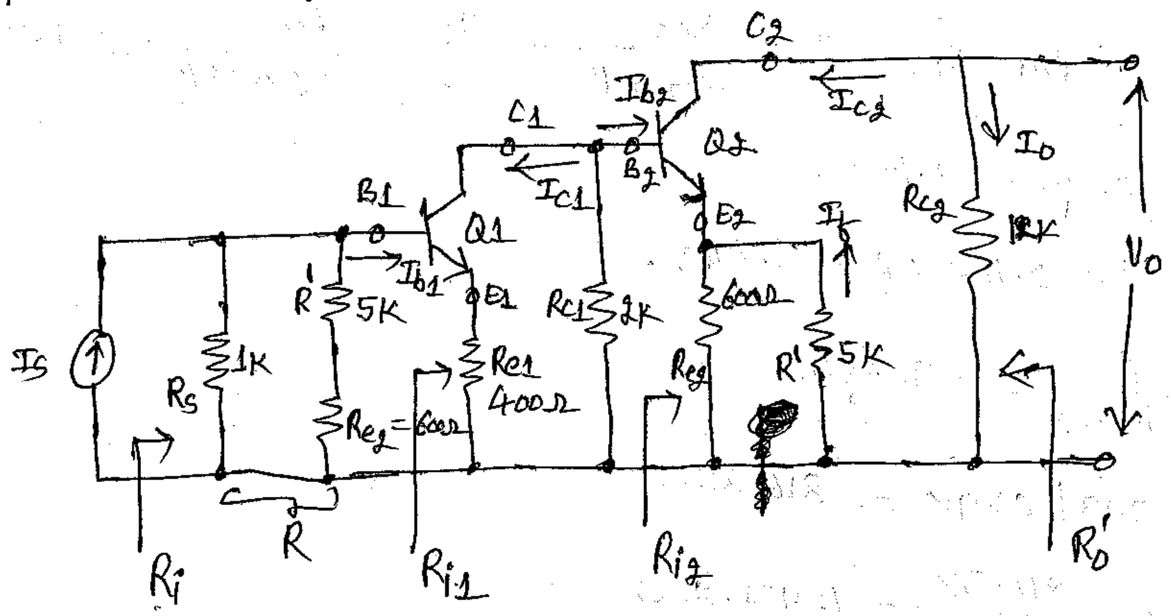
$$R_o' = R_{L2} = 6.6K\Omega$$

$$R_{of}' = \frac{R_o'}{D} = \frac{6.6 \times 10^3}{92.9} = 71.04\Omega$$

problem (2) For the given circuit, calculate A_{if}, A_{vf}, R_{if} and R_{of}.
The transistor h-parameters are $h_{ie} = 1.5K$, $h_{fe} = 50$, $h_{oe} = h_{re} = 0$.

Sol^n:
→ Feedback network is not directly connected to output terminal. So it is current sampling.
→ Feedback network is directly connected to the base or input terminal. So it is shunt mixing.
→ Hence it is a current-shunt feedback amplifier.





$$A_I = \frac{I_o}{I_s} = \frac{-I_{c2}}{I_s} = \frac{-I_{c2}}{I_{b2}} \cdot \frac{I_{b2}}{I_{c1}} \cdot \frac{I_{c1}}{I_{b1}} \cdot \frac{I_{b1}}{I_s}$$

But, $\frac{-I_{c2}}{I_{b2}} = A_{i2} = \frac{-h_{fe}}{1+h_{oe}R_L} = -h_{fe} = -50$ $\{\because h_{oe} = 0\}$

Illy $\frac{-I_{c1}}{I_{b1}} = A_{i1} = -h_{fe} = -50 \Rightarrow \frac{I_{c1}}{I_{b1}} = 50$

$$I_{b2} = -I_{c1} \cdot \frac{R_{c1}}{R_{c1}+R_{i2}} \Rightarrow \frac{I_{b2}}{I_{c1}} = \frac{-R_{c1}}{R_{c1}+R_{i2}}$$

where $R_{i2} = h_{ie} + h_{re} \cdot A_i \cdot R_L = h_{ie} + (1+h_{fe})(R_{e2}\|R') = 28.82K\Omega$.

$$\therefore \frac{I_{b2}}{I_{c1}} = \frac{-2K}{2K+\cancel{28}\,8.2K} = -0.0649 \quad -0.57$$

$$I_{b1} = I_S \cdot \frac{R}{R+R_{i1}} \quad \text{where } R = R_S \| (R'+R_{e1}) = \frac{1K \times 5.6K}{1K+5.6K} = 848\,\Omega$$

$$R_{i1} = h_{ie} + (1+h_{fe}) R_{e1} = 1.5K + (1+50) \times 400 = 21.9K\,\Omega.$$

$$\therefore \frac{I_{b1}}{I_S} = \frac{848}{848+21.9K} = 0.0372. \quad = 0.36$$

$$\therefore A_I = -50 \times (-0.0649) \times 50 \times 0.0372 = 6 \quad 513$$

$$\beta = \frac{I_f}{I_O} \quad \text{But } I_f = I_O \cdot \frac{R_{e2}}{R_{e2}+R'} \Rightarrow \frac{I_f}{I_O} = \frac{600}{600+5K} = 0.107$$

$$\therefore \beta = 0.107.$$

$$I_f = -I_{E_2} \cdot \frac{R_{e2}}{R_{e2}+R'}$$

$$\text{But } -I_{E_2} \approx \cancel{-I_O} = -(-I_o) =$$

$$D = (1+A_I\beta) = 1 + 0.107 \times 6 = 1.642.$$

$$A_{If} = \frac{A_I}{D} = \frac{6}{1.642} = 3.654 \quad 312$$

$$R_i = R \| R_{i1} = 848 \| 21.9K = 816.38\,\Omega \quad 541.73\,\Omega$$

$$\therefore R_{if} = \frac{R_i}{D} = \frac{816.38}{1.642} = 497.2\,\Omega \quad 329.92$$

$$\frac{1}{Z_O} = h_{oe} - \frac{h_{fe} \cdot h_{re}}{h_{ie}+R_S} = 0 \quad \therefore R_o = \frac{1}{Z_O} = \infty.$$

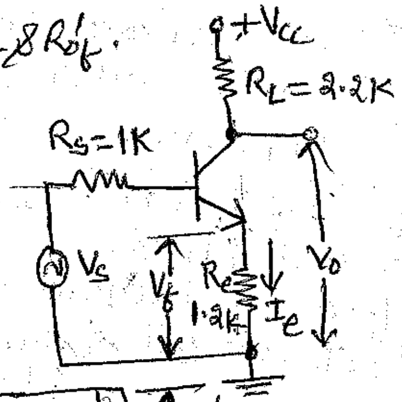
$$\therefore R_{of} = R_o \cdot D = \infty.$$

$$R_o' = R_o \| R_{c2} = \infty \| 12K = 12K.$$

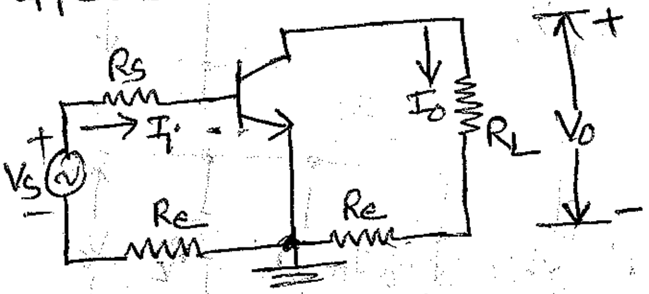
$$\therefore R_{of}' = R_o' \cdot \frac{(1+\beta A_I)}{1+\beta A_I} = R_o' = R_{c2} = 12K\,\Omega.$$

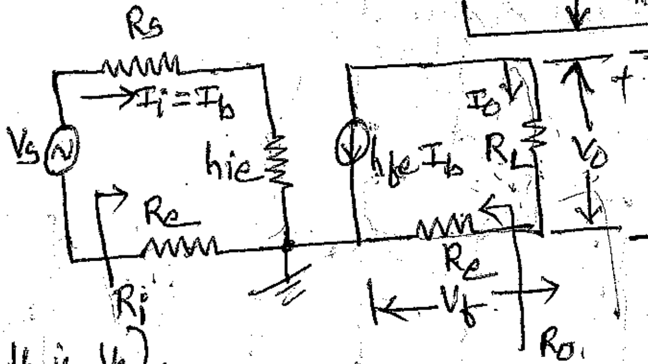
Prob ②: For the circuit shown in figure find G_{mf}, A_{vf}, R_{if} & R'_{of}.

If $h_{ie} = 1.1K\Omega$ & $h_{fe} = 50$.



Soln: It is a current series feedback amplifier.
To find input circuit set $I_o = 0$ then R_e appears at the input side. To find output circuit set $I_i = 0$, then R_e appears in the output circuit.





$$G_m = \frac{I_o}{V_i} = \frac{I_o}{V_s} \quad \{\because V_i \text{ without f/b is } V_s\}$$

$$G_m = \frac{-h_{fe} \cancel{I_b}}{\cancel{I_b}(R_s + h_{ie} + R_e)} = \frac{-50}{10^3 + 1.1\times10^3 + 1.2\times10^3} = \cancel{-0.015}\ -0.045$$

$$\beta = \frac{V_f}{I_o} = \frac{I_e R_e}{I_o} \quad \{\text{But } I_e = -I_o\}$$

$$\beta = -\frac{I_o R_e}{I_o} = -R_e = -1.2\times10^3$$

$$D = 1 + \beta G_m = 1 + (-1.2\times10^3)\times \underset{(-0.015)}{(-0.045)} = 19 \quad 55$$

$$G_{mf} = \frac{G_m}{D} = \frac{\underset{-0.015}{-0.045}}{19} = -0.79\times10^{-3}\ A/V = -0.79\ mA/V \quad -0.8\ mA/V$$

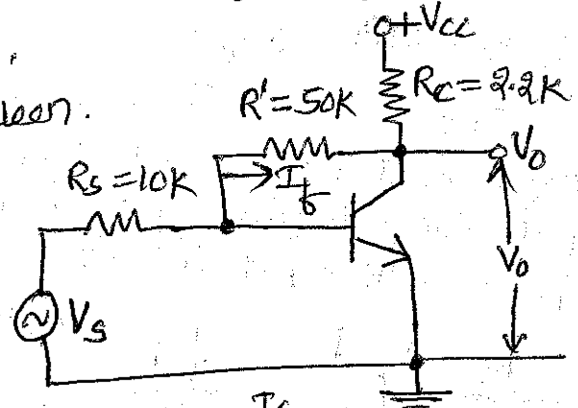
$$A_{vf} = \frac{V_o}{V_s} = \frac{I_o R_L}{V_s} = G_{mf} R_L = -0.79\times10^{-3} \times 2.2\times10^3 = -1.76$$

$$R_i = R_s + h_{ie} + R_e = 1K + 1.1K + 1.2K = 3.3K\Omega \quad 1.1K\Omega$$

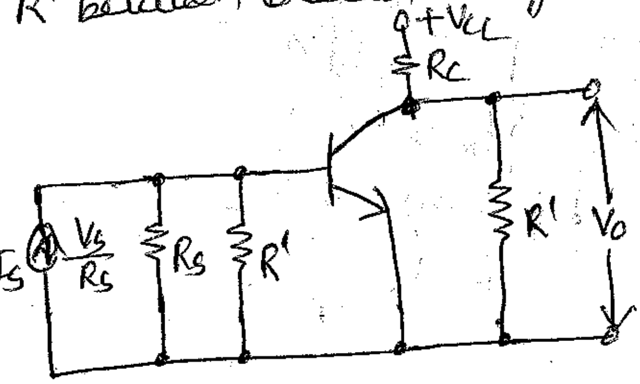
$$R_{if} = R_i D = \underset{1.1K}{3.3\times10^3} \times \underset{\times 55}{19} = \cancel{62.7K\Omega}\ 60.5K\Omega.$$

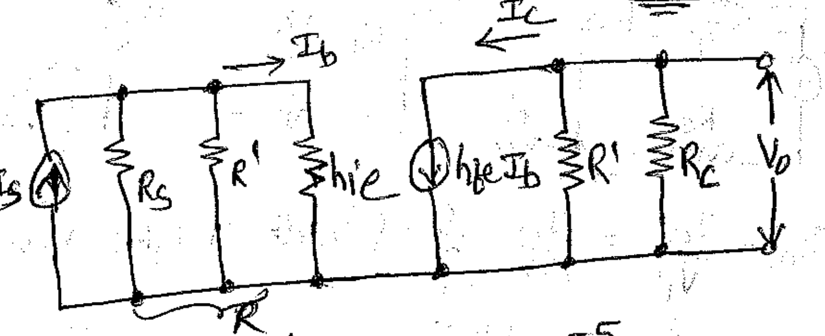
$$R'_{of} = R_L = 2.2K\Omega$$

Prob ④ For the circuit shown in figure calculate R_{mf}, A_{vf}, R_{if} & R_{of}. Assume $h_{ie} = 1.1K\Omega$ & $h_{fe} = 50$.



Soln: It is a voltage shunt feedback amplifier.
To find input circuit set $V_o = 0$ this places R' between base and ground.
To find output circuit set $V_i = 0$ this places R' between collector and ground.





$$I_f = \frac{V_i - V_o}{R'} = \frac{-V_o}{R'} \Rightarrow \frac{I_f}{V_o} = \beta = \frac{-1}{R'} = \frac{-1}{50K} = -2\times10^{-5}$$

$$R_m = \frac{V_o}{I_s} = \frac{-I_c R_c'}{I_s} \quad \text{where } R_c' = R_c \| R' = 2.2K \| 50K = 2.1K\Omega$$

$$\frac{-I_c}{I_s} = \frac{-I_c}{I_b}\cdot\frac{I_b}{I_s} \qquad \frac{-I_c}{I_b} = A_{i1} = -h_{fe} = -50$$

$$\frac{I_b}{I_s} = \frac{R}{R+R_{i1}} \quad \text{where } R = R_s \| R' = 10K \| 50K = 8.33K\Omega$$
$$R_{i1} = h_{ie} = 1.1K\Omega$$

$$\therefore \frac{I_b}{I_s} = \frac{8.33\times10^3}{8.33\times10^3 + 1.1\times10^3} = 0.883$$

$$\therefore R_m = \frac{-I_c R_c'}{I_s} = -\frac{I_c}{I_b}\cdot\frac{I_b}{I_s}\cdot R_c' = -50\times0.883\times2.1\times10^3 = -92.7K$$

$$\therefore D = 1 + R_m\beta = 1 + (-92.7\times10^3)\times(-2\times10^{-5}) = 2.854$$

$$\therefore R_{mf} = \frac{R_m}{D} = \frac{-92.7\times10^3}{2.854} = -32.48K\Omega$$

$$A_{vf} = \frac{V_o}{V_s} = \frac{V_o}{I_s R_s} = \frac{R_{mf}}{R_s} = \frac{-32.48\times10^3}{10\times10^3} = -3.248$$

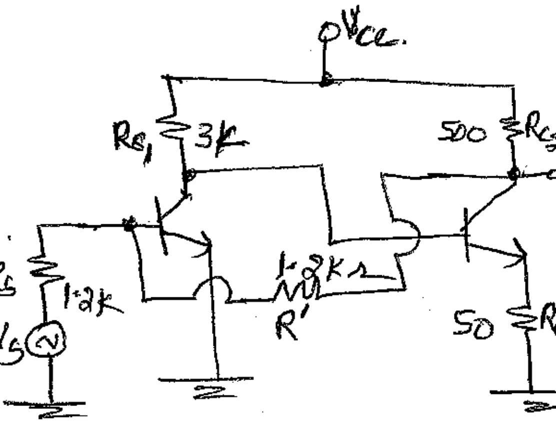
$R_i = R \| R_{i1} = 8.33K \| 1.1K = 971.7\,\Omega$

$R_{if} = R_i / D = \dfrac{971.7}{2.854} = 340.4\cancel{7}\,\Omega$

$R_o = \infty \quad \therefore \quad R_{of} = \dfrac{\infty}{D} = \infty$

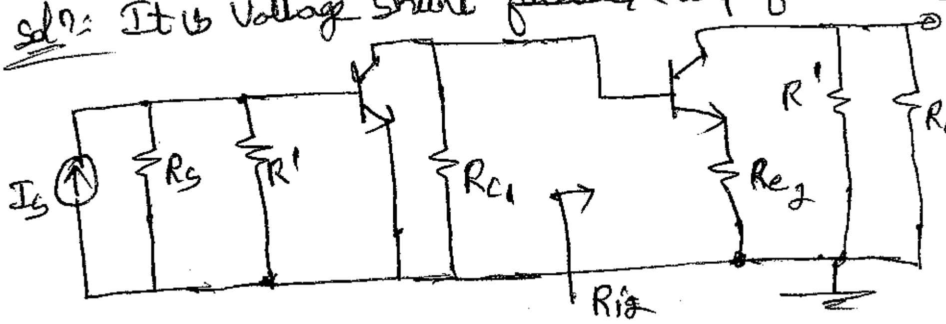
$R_o' = R_o \| R_c' = \infty \| R_c' = R_c' = 2.1K\,\Omega$

$R_{of}' = \dfrac{R_o'}{D} = \dfrac{2.1 \times 10^3}{2.854} = 735.8\,\Omega$



problem: Find R_m & R_{mf} for the circuit shown. $h_{fe} = 50$ & $h_{ie} = 1.1K\Omega$.

soln: It is voltage shunt feedback amplifier.



$R_{i2} = h_{ie} + (1+h_{fe}) R_{e2} = 1.1 \times 10^3 + 51 \times 50 = 3.65K\Omega$

$R_m = \dfrac{V_o}{I_i} = \dfrac{V_o}{I_{b2}} \times \dfrac{I_{b2}}{I_{c1}} \times \dfrac{I_{c1}}{I_{b1}}$

$\dfrac{V_o}{I_{b2}} = -\dfrac{h_{fe} I_{b2} (R_{c2} \| R')}{I_{b2}} = -50 \times (0.5 \times 10^3 \| 1.2 \times 10^3) = -17.6 \times 10^3$

$-\dfrac{I_{c1}}{I_{b1}} = A_{i1} = -h_{fe} \Rightarrow \dfrac{I_{c1}}{I_{b1}} = 50$

$\dfrac{I_{b2}}{I_{c1}} = \dfrac{-R_{c1}}{R_{c1} + R_{i2}} = \dfrac{-3 \times 10^3}{3 \times 10^3 + 3.65 \times 10^3} = -0.451$

$R_{i1} = h_{ie} = 1.1K\Omega$

$R_m = -17.6 \times 10^3 \times -0.451 \times 50 = 396.9K\Omega$

$\beta = \dfrac{I_f}{V_o} = \dfrac{1}{R'} = \dfrac{1}{1.2 \times 10^3} = 0.833 \times 10^{-3}$

$R_{mf} = \dfrac{R_m}{1 + R_m \beta} = \dfrac{396.9 \times 10^3}{1 + 396.9 \times 10^3 \times 0.833 \times 10^{-3}} = 1.199K\Omega$

→ The positive feedback results into oscillations and hence used in electronic circuits to generate the oscillations of desired frequency. Such circuits are called oscillators.

→ The gain with feedback is given as, $A_f = \frac{A}{1-A\beta}$

→ For constant open loop gain 'A', the gain with feedback 'A_f' increases as the amount of positive feedback 'β' increases.

→ In limiting case, the gain becomes infinite. This indicates that the circuit can produce output without external input $V_s = 0$, just by feeding the part of the output as its own input.

→ Similarly, output cannot be infinite but gets driven into the oscillations.

In otherwords, the circuit stops amplifying and starts oscillating.

→ Thus without an input, the output will continue to oscillate whose frequency depends upon the feedback network or the amplifier or both. Such a circuit is called an oscillator.

→ The feedback ratio 'β' is always a fraction and hence $\beta < 1$. So the feedback network is an attenuation network.

→ To start with the oscillations $A\beta > 1$ but the circuit adjusts itself to get $A\beta = 1$, when it produces sinusoidal oscillations while working as an oscillator.

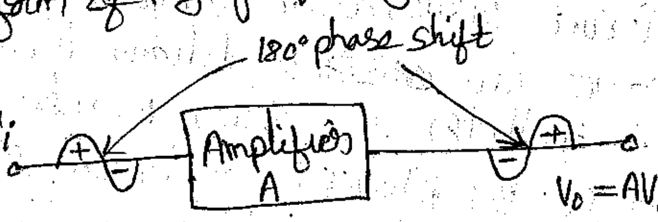
→ An oscillator is an amplifier, which uses a positive feedback and without any external input signal, generates an output waveform, at a desired frequency.

→ An oscillator is a circuit which basically acts as a generator, generating the output signal which oscillates with constant amplitude and constant desired frequency.

→ An oscillator does not require any input signal.

→ An oscillator can generate the output waveform of high frequency upto GHz.

Barkhausen criterion ;



→ Consider a basic inverting amplifier with an open loop gain A. The feedback network attenuation factor 'β' is less than unity.

Fig: Inverting amplifier.

→ As basic amplifier is inverting, it produces a phase shift of 180° between input and output as shown in figure.

→ Now the input V_i applied to the amplifier is to be derived from its output 'V_o' using feedback network.

→ But the feedback must be positive i.e the voltage derived from output using feedback network must be in phase with V_i. Thus the feedback network must introduce a phase shift of 180° while feedback the voltage from output to input. This ensures positive feedback.

→ Consider a fictitious voltage 'V_i' applied at the input of the amplifier. Here we get, $V_0 = AV_i$ —— ①

→ The feedback factor 'β' decides the feedback to be given to the input, i.e $V_f = \beta V_0$ —— ②

Substituting ① in ② we get,

$V_f = A\beta V_i$ —— ③

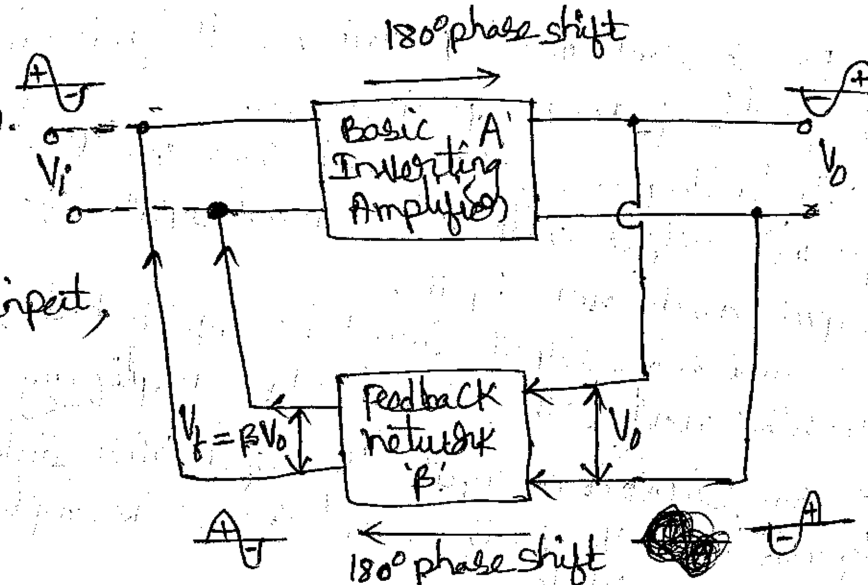


Fig: Basic block diagram of oscillator circuit

→ For the oscillator, we want that feedback should drive the amplifier and hence 'V_f' must act as V_i. we can write that, V_f is sufficient to act as V_i when,

From eqn ③ we can write that

$|A\beta| = 1$ —— ④

and the phase of V_f is same as V_i i.e feedback network should introduce 18 phase shift in addition to 180° phase shift introduced by inverting amplifie. So total phase shift around a loop is 36

→ This ensures positive feedback.

→ In this condition, V_f drives the circuit and without external input circuit works as an oscillator.

→ The two conditions discussed above, required to work the circuit a an oscillator are called Barkhausen criterion for oscillation.

→ The Barkhausen criterion states that,

(i) the total phase shift around a loop, as the signal proceeds from inpu through amplifier, feedback network, back to input gain, completing a loop i precisely 0° or 360°.

(ii) The magnitude of the product of open loop gain of the amplifier 'A' and the magnitude of feedback factor 'β' is unity i.e $|A\beta| = 1$.

→ satisfying the Barkhausen criterion, the circuit works as an oscillator producing sustained oscillations of constant frequency and amplitude.

→ In reality, no input signal is needed to start the oscillations. In practice, $A\beta$ is made greater than one to ~~start~~ start the oscillations and then circuit adjusts itself to get $A\beta = 1$, finally resulting into self sustained oscillations.

Effect of Loop Gain "$A\beta$" on the nature of the oscillations:

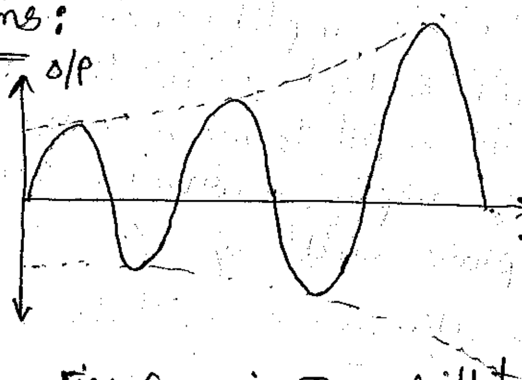


Fig: Growing Type oscillations

① $|A\beta| > 1$:

when the total phase shift around a loop is $0°$ or $360°$ and $|A\beta| > 1$, then the output oscillates but the oscillations are of growing type. The amplitude of oscillations goes on increasing as shown in figure.

② $|A\beta| = 1$:

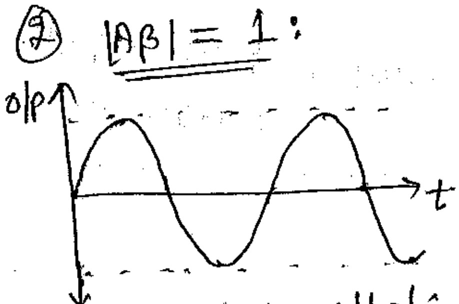


Fig: Sustained oscillations

As stated by Barkhausen criterion, when total phase shift around a loop is $0°$ or $360°$ ensuring positive feedback and $|A\beta| = 1$ then the oscillations are with constant frequency and amplitude called sustained oscillations.

③ $|A\beta| < 1$:

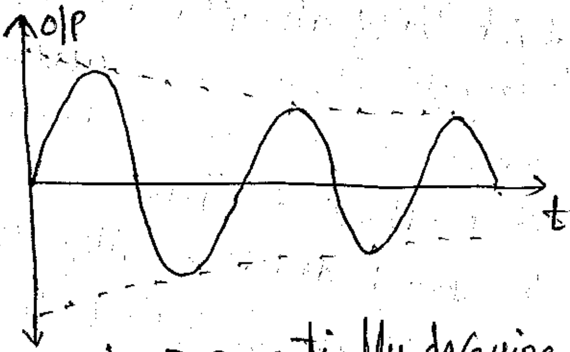


Fig: Exponentially decaying oscillations.

when the total phase shift around a loop is $0°$ or $360°$ but $|A\beta| < 1$ then the oscillations are of decaying type i.e such oscillation amplitude decreases exponentially and the oscillations finally cease. Thus circuit works as an amplifier without oscillations. The decaying oscillations are as shown in figure.

→ So to start the oscillations without input, $|A\beta|$ is kept higher than unity and then circuit adjusts itself to get $|A\beta| = 1$ to result sustained oscillations

Starting Voltage:

→ Every resistance has some free electrons. Under the influence of normal room temperature, these free electrons move randomly in various directions. Such a movement of the free electrons generate a voltage called noise voltage, across the resistance. Such noise voltages present across the resistances are amplified. Hence to amplify such small noise voltages and to start the oscillations, $|A\beta|$ is kept greater than unity at start. Such amplified voltage appears at the output terminals. The part of this output is sufficient to drive the inpu[t] of amplifier circuit. Then circuit adjusts itself to get $|A\beta| = 1$ and with phase shift of 360° we get sustained oscillations.

Classification of oscillators:

(1) Based on the output waveform generated,

(a) Sinusoidal oscillators

(b) Non-sinusoidal (or) Relaxation oscillators.

→ The sinusoidal oscillators generate purely sinusoidal waveform at the output while the non-sinusoidal or relaxation oscillators generates waveforms which vary abruptly one or more times in a cycle of oscillation such as triangular, square, sawtooth etc.

(2) Based on whether feedback is used or not,

(a) Feedback oscillators

(b) Non-feedback (or) Negative resistance oscillators.

→ The oscillators in which the feedback is used & which satisfies Barkhaus[en] criterion are classified as feedback oscillators.

→ The oscillators in which the feedback is not used to generate the oscillatio[ns] are classified as non-feedback oscillators. The non-feedback oscillators use th[e] negative resistance region of the characteristics of the device used. Hence the[y] are also called as Negative resistance oscillators.

(3) Based on the circuit components used,

(a) RC phase shift oscillators

(b) LC tuned oscillators.

(c) Crystal oscillators.

→ The oscillators using the components resistance 'R' and capacitor 'C' are calle[d] RC oscillators. While the oscillators using the components inductance 'L' and capaci[tor] 'C' are called LC oscillators. In some oscillators crystal is used, which are called crystal oscillators.

(4) Based on the Range of operating frequency,

(a) Audio frequency oscillator (AFO) : upto 20 KHz
(b) Radio frequency oscillator (RFO) : 20 KHz to 30 MHz
(c) Very High frequency (VHF) oscillator : 30 MHz to 300 MHz
(d) ultra High frequency (UHF) oscillator : 300 MHz to 3 GHz
(e) Microwave frequency oscillator : above 3 GHz.

LC-oscillators:

→ The oscillators which use the elements 'L' and 'c' to produce the oscillations are call[ed] LC oscillators. The circuit using elements 'L' and 'c' is called tank circuit or oscillatory circuit, which is an important part of LC oscillators. This circuit is also referred as resonating circuit or tuned circuit. These oscillations are u[sed] for high frequency range. Due to high frequency range, these oscillators are ofte[n] used for sources of RF (Radio frequency) energy.

operation of LC-Tank circuit:

→ The LC tank circuit consists of elements L and C connected in parallel as show[n] in figure.

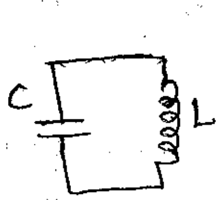


Fig: (a) LC Tank circuit

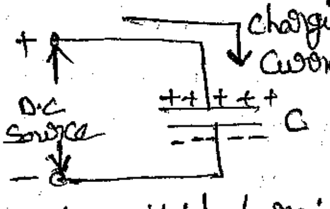


Fig: (b) Initial charging

→ Let the capacitor is initially charged from a d.c source with the polarities as shown in figure (b).
→ when the capacitor gets charged, the energy gets stored in a capacitor called electrostatic energy.
→ when such a charged capacitor is connected across inductor 'L' in a tank circuit, the capacitor starts discharging through 'L' as shown in fig (c). The arrow indicates the flow of conventional current.
→ Due to such current flow, the magnetic field gets set up around the inductor 'L'. Thus inductor starts storing the energy.
→ when capacitor is fully discharged, maximum current flows through the circuit. At this instant all the electrostatic energy get stored as a magnetic energy in the inductor 'L' as shown in fig (d).

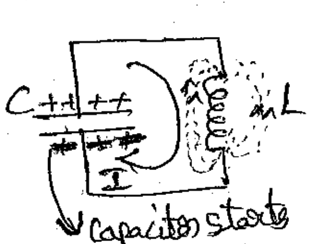


Fig (c)

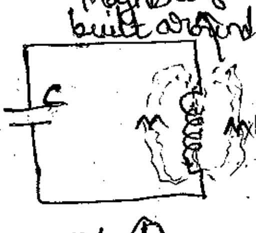


Fig (d).

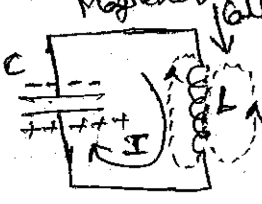


Fig (e)

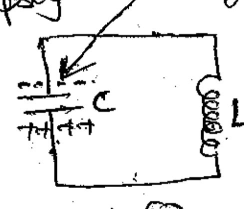


Fig (f)

→ Now the magnetic field around 'L' starts collapsing. As per Lenz's law, this starts charging the capacitor with opposite polarity making lower plate positive and upper plate negative as shown in fig (e).

→ After some time, capacitor gets fully charged with opposite polarities as compared to its initial polarities as shown in figure (f). The entire magnetic energy gets converted back to electrostatic energy in capacitor.

→ Now capacitor again starts discharging through inductor 'L'. But the direction of current through circuit is now opposite to the direction of current earlier in the circuit. This is shown in fig (f).

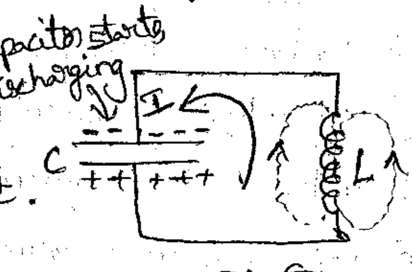


Fig: (g)

→ Again electrostatic energy is converted to magnetic energy. When capacitor is fully discharged, the magnetic field starts collapsing, charging the capacitor again in opposite direction.

→ Thus capacitor charges with alternate polarities and discharges producing alternating current in the tank circuit.

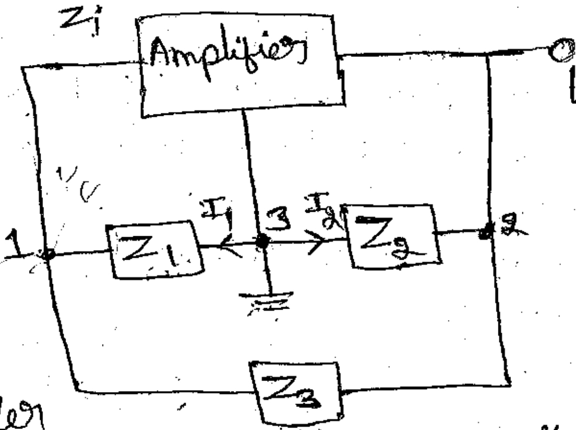
→ This is nothing but oscillatory current. But every time when energy is transferred from 'C' to 'L' and 'L' to 'C', the losses occur due to which amplitude of oscillating current keeps on decreasing everytime when energy transfer takes place.

→ Here actually we get exponentially decaying oscillations called damped oscillations. Such oscillations stop after sometime.

→ In LC-oscillator, the transistor amplifier supplies this loss of energy at proper times.

→ The care of proper polarity is taken by the feedback network. Thus LC tank circuit alongwith transistor amplifier can be used to obtain oscillators called LC-oscillators. Due to supply of energy which is lost, the oscillations get maintained hence called sustained oscillations or undamped oscillations.

Basic form of LC oscillator circuit:



→ In the general form of oscillator circuit, any of the active devices such as vacuum tubes, BJT, FET and operational amplifier may be used in the amplifier section.

→ Z_1, Z_2 and Z_3 are reactive elements constituting the feedback tank circuit which determines the frequency of oscillation.

→ Here Z_1 and Z_2 serve as an a.c voltage divider for the output voltage and feedback signal. Therefore, the voltage across Z_1 is the feedback signal. The frequency of oscillations of the LC oscillator is,

$$f_0 = \frac{1}{2\pi\sqrt{LC}}$$

→ The inductive and capacitive reactances are represented by Z_1, Z_2 and Z_3. The output terminals are 2 and 3, and input terminals are 1 and 3.

Load impedance: Since z_1 and the input impedance h_{ie} of the transistor are in parallel their equivalent impedance z' is given by,

$$z' = \frac{z_1 h_{ie}}{z_1 + h_{ie}}$$

Now the load impedance z_L between the output terminals 2 and 3 is the equivalent impedance of z_2 in parallel with the series combination of z' and z_3

$$\therefore \frac{1}{z_L} = \frac{1}{z_2} + \frac{1}{z' + z_3}$$

$$= \frac{1}{z_2} + \frac{1}{\frac{z_1 h_{ie}}{z_1 + h_{ie}} + z_3}$$

$$= \frac{1}{z_2} + \frac{z_1 + h_{ie}}{z_1 h_{ie} + z_1 z_3 + z_3 h_{ie}}$$

$$= \frac{1}{z_2} + \frac{z_1 + h_{ie}}{h_{ie}(z_1 + z_3) + z_1 z_3}$$

$$\frac{1}{z_L} = \frac{h_{ie}(z_1 + z_3) + z_1 z_3 + z_1 z_2 + z_2 h_{ie}}{z_2[h_{ie}(z_1 + z_3) + z_1 z_3]}$$

$$\Rightarrow z_L = \frac{z_2[h_{ie}(z_1 + z_3) + z_1 z_3]}{h_{ie}(z_1 + z_2 + z_3) + z_1 z_2 + z_1 z_3}$$

Voltage gain without feedback is given as, $A_V = \frac{-h_{fe} z_L}{h_{ie}}$

Feedback fraction 'β':

The output voltage between the terminals 3 and 2 in terms of the current I_1 is given by,

$$V_o = -I_1(z' + z_3) = -I_1\left(\frac{z_1 h_{ie}}{z_1 + h_{ie}} + z_3\right)$$

$$\Rightarrow V_o = -I_1 \frac{(z_1 + z_3) h_{ie} + z_1 z_3}{z_1 + h_{ie}}$$

The voltage feedback to the input terminals 3 and 1 is given by,

$$V_{fb} = -I_1 z' = -I_1 \frac{z_1 h_{ie}}{z_1 + h_{ie}}$$

Therefore, the feedback ratio 'β' is given by,

$$\beta = \frac{V_{fb}}{V_o} = \cancel{I_1}\frac{z_1 h_{ie}}{\cancel{z_1+h_{ie}}} \times \frac{\cancel{z_1+h_{ie}}}{\cancel{I_1}\,h_{ie}(z_1+z_3)+z_1z_3}$$

$$\beta = \frac{z_1 h_{ie}}{h_{ie}(z_1+z_3)+z_1z_3}$$

Equation for the oscillator:

For oscillation we must have $A\beta = 1$

$$\therefore \frac{-h_{fe} Z_L}{\cancel{h_{ie}}} \times \frac{z_1 \cancel{h_{ie}}}{h_{ie}(z_1+z_3)+z_1z_3} = 1$$

$$\therefore \frac{h_{fe} z_2\,\cancel{[h_{ie}(z_1+z_3)+z_1z_3]}}{h_{ie}(z_1+z_2+z_3)+z_1z_2+z_1z_3} \times \frac{z_1}{\cancel{[h_{ie}(z_1+z_3)+z_1z_3]}} = -1$$

$$\frac{h_{fe} z_1 z_2}{h_{ie}(z_1+z_2+z_3)+z_1z_2+z_1z_3} = -1$$

$$\Rightarrow h_{ie}(z_1+z_2+z_3)+z_1z_2+z_1z_3 = -h_{fe} z_1 z_2.$$

$$\Rightarrow \boxed{h_{ie}(z_1+z_2+z_3)+(1+h_{fe})z_1z_2+z_1z_3=0}$$

This is the general equation for the oscillator.

Hartley oscillator:

→ A LC oscillator which uses two inductive reactances and one capacitive reactance in its feedback network is called Hartley oscillator.

→ The amplifier stage uses an active device as a transistor in common emitter configuration.

→ The resistances R_1 and R_2 are the biasing resistances.

→ The RFC is the radiofrequency choke. Its reactance value is very high for high frequencies, hence it can be treated as open circuit. while for d.c conditions, the reactance is zero hence causes no problem for d.c capacitors.

→ Here due to RFC, the isolation between a.c and d.c operation is achieved. R_E is also a biasing circuit resistance and C_E is the emitter bypass circuit. C_1 and C_2 are the coupling capacitors.

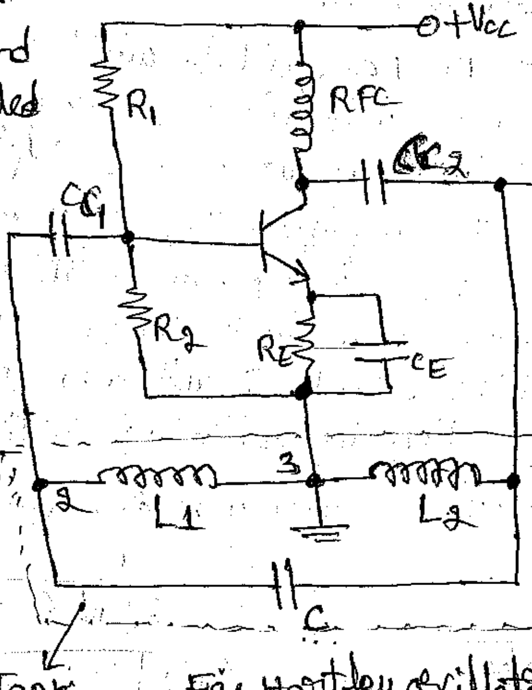


Fig: Hartley oscillator

→ The common emitter amplifier provides a phase shift of 180°. As emitter is grounded, the base and the collector voltages are out of phase by 180°. As the centre of L_1 and L_2 is grounded, when upper end becomes positive, the lower becomes negative and vice-versa. So the LC feedback network gives an additional phase shift of 180°, necessary to satisfy oscillation conditions.

→ The frequency of oscillations is given as, $f = \frac{1}{2\pi\sqrt{(L_1+L_2)C}}$

→ To satisfy the oscillating conditions, $h_{fe} = \frac{L_1}{L_2}$.

→ for a mutual inductance of M, $h_{fe} = \frac{L_1+M}{L_2+M}$

If $L_{eq} = L_1+L_2$ then $f = \frac{1}{2\pi\sqrt{CL_{eq}}}$

→ so if the capacitor 'C' is kept variable, frequency can be varied over a large range as per the requirement.

In practice L_1 and L_2 may be wound on a single core so that there exists a mutual inductance between them denoted as M.

→ In such a case, the mutual inductance is considered while determining the equivalent inductance L_{eq}.

$$\therefore L_{eq} = L_1 + L_2 + 2M$$

→ If L_1 and L_2 are assisting each other then sign of 2M is positive while if L_1 and L_2 are in series opposition then sign of 2M is negative.

Colpitts oscillator:

→ An LC-oscillator which uses two capacitive reactances and one inductive reactance in the feedback network i.e. tank circuit is called Colpitts oscillator.

→ The amplifier stage uses an active device as a transistor in common emitter configuration.

→ The CE amplifier causes a phase shift of 180°, while the tank circuit adds further 180° phase shift to satisfy the oscillating conditions.

→ The frequency of oscillations is given as,

$$f = \frac{1}{2\pi\sqrt{L C_{eq}}}$$

where $C_{eq} = C_1 C_2 / (C_1 + C_2)$

To satisfy the oscillating conditions, $h_{fe} = \frac{C_2}{C_1}$.

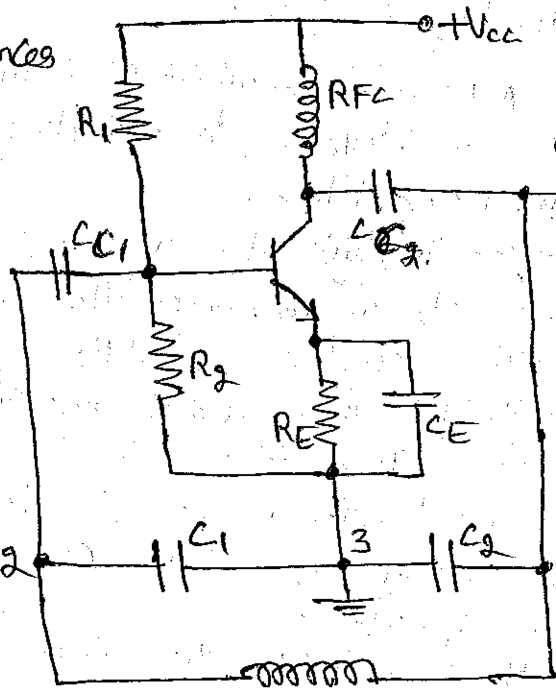


Fig: Colpitts oscillat

Clapp oscillator:

→ To achieve the frequency stability, Colpitts oscillator circuit is slightly modified in practice called clapp oscillator.

→ The basic tank circuit with two capacitive reactances and one inductive reactance remains same. But the modification in the tank circuit is that one more capacitor C_3 is introduced in series with the inductance as shown in figure.

→ The value of C_3 is much smaller than the values of C_1 and C_2.

→ The frequency of oscillations is given as,

$$f = \frac{1}{2\pi\sqrt{L C_{eq}}} \quad \left\{ \text{where } \frac{1}{C_{eq}} = \frac{1}{C_1} + \frac{1}{C_2} + \frac{1}{C_3} \right\}$$

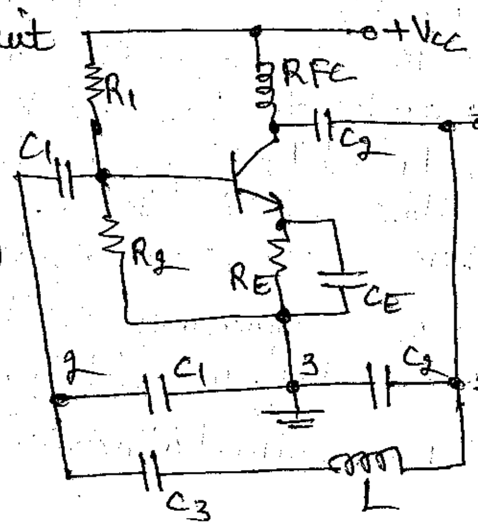


Fig: clapp oscillat

→ The frequency of clapp oscillator is stable and accurate. The transistor and stray capacitances have no effect on C_3, hence good frequency stability is achiev in clapp oscillator.

→ Another advantage of C_3 is that it can be kept variable. As frequency is dependent on C_3, the frequency can be varied in the desired range.

→ As C_3 is much less than C_1 and C_2 then $C_{eq} = C_3$.

$$\therefore f = \frac{1}{2\pi\sqrt{L C_3}}$$

Derivation of frequency of oscillations for Hartley oscillator:

z_1 and z_2 are inductive reactances and z_3 is the capacitive reactance. Suppose 'M' is the mutual inductance between the inductors, then

$$z_1 = j\omega L_1 + j\omega M,\ z_2 = j\omega L_2 + j\omega M,\ z_3 = \frac{1}{j\omega C} = \frac{-j}{\omega C}$$

The general equation for oscillations is,

$$h_{ie}(z_1+z_2+z_3) + z_1 z_2(1+h_{fe}) + z_1 z_3 = 0$$

$$\Rightarrow h_{ie}\, j\omega\left[L_1+M+L_2+M - \frac{1}{\omega^2 C}\right] + (1+h_{fe})(j\omega)^2(L_1+M)(L_2+M) - \frac{j}{\omega C}\times j\omega(L_1+M) = 0.$$

$$\Rightarrow j\omega h_{ie}\left[L_1+L_2+2M - \frac{1}{\omega^2 C}\right] - \omega^2(1+h_{fe})(L_1+M)(L_2+M) + \frac{1}{C}(L_1+M) = 0$$

$$\Rightarrow j\omega h_{ie}\left[L_1+L_2+2M - \frac{1}{\omega^2 C}\right] - \omega^2(L_1+M)\left[(L_2+M)(1+h_{fe}) - \frac{1}{\omega^2 C}\right] = 0$$

The frequency of oscillation $f_0 = \frac{\omega_0}{2\pi}$ can be determined by equating the imaginary part to zero.

$$\therefore\ L_1+L_2+2M - \frac{1}{\omega_0^2 C} = 0.$$

$$\Rightarrow f_0 = \frac{\omega_0}{2\pi} = \frac{1}{2\pi\sqrt{(L_1+L_2+2M)C}}$$

The condition for maintenance of oscillation is obtained equating real part to zero

$$\therefore (L_2+M)(1+h_{fe}) - \frac{1}{\omega_0^2 C} = 0$$

$$\Rightarrow (L_2+M)(1+h_{fe}) = L_1+L_2+2M.$$

$$1+h_{fe} = \frac{L_1+L_2+2M}{L_2+M}.$$

$$\Rightarrow \boxed{h_{fe} = \frac{L_1+M}{L_2+M}}$$

Prob①: In the Hartley oscillator $L_2 = 0.4mH$ and $C = 0.004\mu F$. If the frequency of the oscillator is 120 KHz find the value of L_1. Neglect the mutual inductance.

Soln:
$$f_0 = \frac{1}{2\pi\sqrt{(L_1+L_2)C}}$$

$$120 \times 10^3 = \frac{1}{2\pi \times \sqrt{(L_1 + 0.4\times10^{-3}) \times 0.004\times10^{-6}}}$$

$$\Rightarrow L_1 = \underline{0.04mH}.$$

Prob②: In a Hartley oscillator, the value of capacitor in the tuned circuit is 500 PF and two sections of coil have inductances 38μH and 12μH. find the frequency of oscillations and the feedback factor β.

Soln:
$$f_0 = \frac{1}{2\pi\sqrt{LC}}$$

$$L = L_1 + L_2 = 38\mu + 12\mu = 50\mu H \quad \& \quad C = 500PF$$

$$\therefore f_0 = \frac{1}{2\pi \times \sqrt{50\times10^{-6} \times 500\times10^{-12}}} = 1MHz$$

$$\beta = \frac{L_1}{L_2} = \frac{38\times10^{-6}}{12\times10^{-6}} = 3.166$$

Prob③: In a Hartley oscillator. $L_1 = 2mH$, $L_2 = 20\mu H$. when the frequency is to be changed from 950KHz to 2050KHz find the range over which the capacitor is to be varied.

Soln:
$$f_0 = \frac{1}{2\pi\sqrt{(L_1+L_2)C}}$$

when $f_0 = 950KHz$,
$$950\times10^3 = \frac{1}{2\pi\times\sqrt{(2\times10^{-3}+20\times10^{-6})C}} \Rightarrow C = 13.89PF$$

when $f_0 = 2050KHz$,
$$2050\times10^3 = \frac{1}{2\pi\times\sqrt{(2\times10^{-3}+20\times10^{-6})C}} \Rightarrow C = 2.98PF$$

Hence, the range of capacitance is from 2.98PF to 13.89PF.

Derivation of frequency of oscillations of Colpitts oscillator:

$$z_1 = \frac{1}{j\omega C_1} = \frac{-j}{\omega C_1}\ ;\ z_2 = \frac{1}{j\omega C_2} = \frac{-j}{\omega C_2} \text{ and } z_3 = j\omega L$$

The general equation for oscillations is,

$$h_{ie}(z_1+z_2+z_3) + z_1 z_2(1+h_{fe}) + z_1 z_3 = 0$$

$$\Rightarrow h_{ie}\left[\frac{-j}{\omega C_1} + \frac{-j}{\omega C_2} + j\omega L\right] + (1+h_{fe})\left[\frac{-j}{\omega C_1}\times\frac{-j}{\omega C_2}\right] + \left[\frac{-j}{\omega C_1}\times j\omega L\right] = 0$$

$$-jh_{ie}\left[\frac{1}{\omega C_1} + \frac{1}{\omega C_2} - \omega L\right] + \left[\frac{1+h_{fe}}{\omega^2 C_1 C_2} - \frac{L}{C_1}\right] = 0.$$

The frequency of oscillation $f_0 = \frac{\omega_0}{2\pi}$ is found by equating the imaginary part to zero.

$$\therefore \frac{1}{\omega_0 C_1} + \frac{1}{\omega_0 C_2} - \omega_0 L = 0$$

$$\Rightarrow \omega_0 L = \frac{1}{\omega_0 C_1} + \frac{1}{\omega_0 C_2}$$

$$\Rightarrow \omega_0^2 = \frac{1}{L C_{eq}} \qquad \left\{\text{where } \frac{1}{C_{eq}} = \frac{1}{C_1} + \frac{1}{C_2}\right\}$$

$$\therefore f_0 = \frac{1}{2\pi\sqrt{L C_{eq}}}$$

The condition for maintenance of oscillation is obtained by equating to zero the real part:

$$\therefore \frac{1+h_{fe}}{\omega^2 \cancel{C_1} C_2} = \frac{L}{\cancel{C_1}}$$

$$\Rightarrow h_{fe} = \omega^2 L C_2 - 1 \qquad \left\{\because \omega L = \frac{1}{\omega C_1} + \frac{1}{\omega C_2}\right\}$$

$$= \cancel{\omega} C_2\left[\frac{1}{\cancel{\omega} C_1} + \frac{1}{\cancel{\omega} C_2}\right] - 1$$

$$= \cancel{C_2}\,\frac{C_1 + C_2}{C_1 \cancel{C_2}} - 1$$

$$h_{fe} = \frac{\cancel{C_1} + C_2 - \cancel{C_1}}{C_1}$$

$$\boxed{h_{fe} = \frac{C_2}{C_1}}$$

prob ①: In a Colpitts oscillator $L = 40\,mH$, $C_1 = 100\,pF$ and $C_2 = 500\,pF$. find the frequency of oscillations.

Soln: $f_0 = \frac{1}{2\pi\sqrt{L C_{eq}}}$ $C_{eq} = \frac{C_1 C_2}{C_1 + C_2} = \frac{100\times10^{-12} \times 500\times10^{-12}}{100\times10^{-12} + 500\times10^{-12}}$

$C_{eq} = 83.33\,pF$.

$$f_0 = \frac{1}{2\pi \times \sqrt{40\times10^{-3} \times 83.33\times10^{-12}}}$$

$f_0 = 87.17\,KHz$.

prob ②: In Colpitts oscillator $C_1 = 0.2\mu F$ and $C_2 = 0.02\mu F$. If frequency of oscillations is $10\,KHz$ find the value of inductor.

Soln: $C_{eq} = \frac{C_1 C_2}{C_1 + C_2} = \frac{0.2\mu \times 0.02\mu}{0.2\mu + 0.02\mu} = 18.18\,nF$

$$f_0 = \frac{1}{2\pi\sqrt{L\, C_{eq}}}$$

$\Rightarrow 10\times10^3 = \frac{1}{2\pi \times \sqrt{L \times 18.18\times10^{-9}}} \Rightarrow L = 13.93\,mH$.

prob ③: A Colpitts oscillator is designed with $C_1 = 100\,pF$ and $C_2 = 7500\,pF$. Find the range of inductance values if the frequency of oscillation varies from $950\,KHz$ to $2050\,KHz$.

Soln: $C_{eq} = C_1 || C_2 = 100p \,||\, 7500p = 98.68\,pF$. $f_0 = \frac{1}{2\pi\sqrt{L C_{eq}}}$

when $f_0 = 950\,KHz$,

$950\times10^3 = \frac{1}{2\pi \times \sqrt{L \times 98.68\times10^{-12}}} \Rightarrow L = 284\,\mu H$.

when $f_0 = 2050\,KHz$,

$2050\times10^3 = \frac{1}{2\pi \times \sqrt{L \times 98.68\times10^{-12}}} \rightarrow L = 61\,\mu H$.

Hence the range of inductance required is from $61\,\mu H$ to $284\,\mu H$.

RC phase shift oscillator:

→ The RC phase shift oscillator consists of an amplifier and a RC feedback network consisting of resistors and capacitors arranged in ladder fashion. Hence such oscillator also called ladder type RC phase shift oscillator.

• In oscillator, feedback network must introduce a phase shift of 180° to obtain total phase shift around a loop as 360°. Thus if one RC network produces phase shift of $\phi = 60°$ then to produce phase shift of 180° such three RC networks must be connected in cascade.

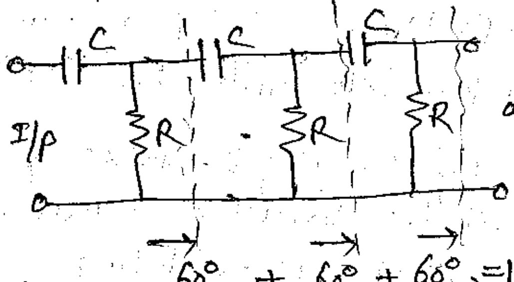


Fig: RC Feedback Network

→ Hence in RC phase shift oscillator, the feedback network consists of three RC sections each producing a phase shift of 60°, thus total phase shift due to feedback is 180°.

• The network is also called the ladder network. All the resistance values and all the capacitance values are same, so that for a particular frequency, each section of R and C produces a phase shift of 60°.

→ In a practical RC phase shift oscillator, a CE amplifier is used as a basic amplifier. This produces 180° phase shift. The feedback network consists of three RC sections each producing 60° phase shift. Such a RC phase shift oscillator using BJT is as shown in figure.

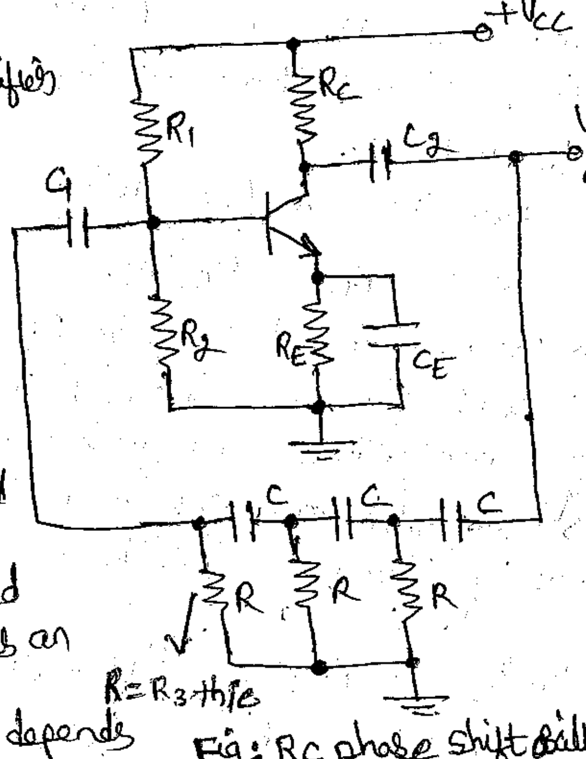


Fig: RC phase shift oscillator

$R_i = h_{ie}$ & $R_i' = R_1 \| R_2 \| h_{ie}$

$R = h_{ie} + R_3$

→ The output of amplifier is given to feedback network. The output of the feedback network drives the amplifier. The total phase shift around a loop is 180° of amplifier and 180° due to three RC sections, thus 360°. This satisfies the required condition for positive feedback and circuit works as an oscillator.

→ The frequency of sustained oscillations generated depends on the values of R and C and is given by,

$$f = \frac{1}{2\pi RC\sqrt{6}} \text{ Hz.}$$

• Actually to satisfy the Barkhausen condition, the expression for the frequency of oscillations is given by,

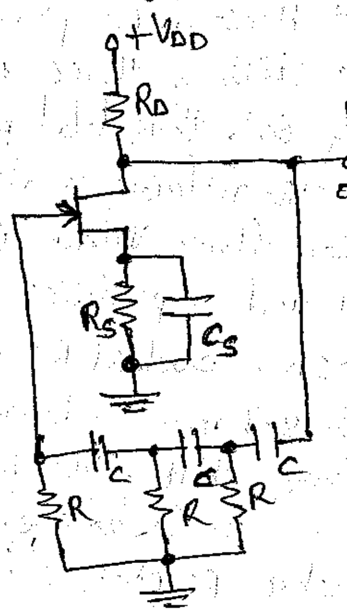
$$f = \frac{1}{2\pi RC\sqrt{6+4K}} \quad \text{where } K = \frac{R_C}{R}.$$

→ As practically R_c/R is small, K is neglected.
→ The condition of h_{fe} for the transistor to obtain the oscillations is given by

$$h_{fe} > 4K + 23 + \frac{29}{K}$$

→ And value of 'K' for minimum h_{fe} is 2.7. Hence minimum $h_{fe} = 44.5$.
So transistor with h_{fe} less than 44.5 cannot be used in phase shift oscillator.
→ By changing the values of R and C, the frequency of the oscillator can be changed. But the values of R and C of all three sections must be changed simultaneously to satisfy the oscillating conditions. But this is practically impossible. Hence the phase shift oscillator is considered as a fixed frequency oscillator, for all practical purposes.

FET phase shift oscillator:

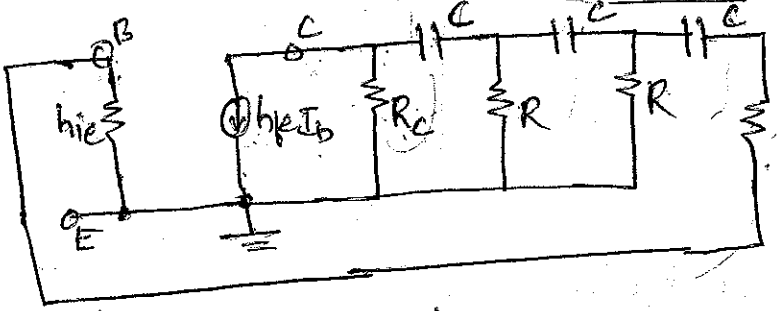


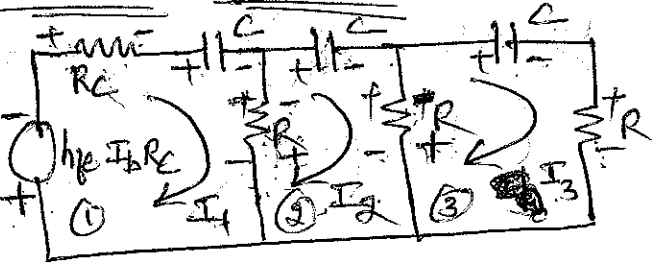
→ For the amplifier stage FET is used. It is self biased with a capacitor bypassed source resistance R_S and a drain bias resistance R_D. The important parameters of FET are g_m and r_d.
→ From FET amplifier theory we have, $|A| = g_m R_L$
where $R_L = R_D \| r_d$.
→ The input impedance of the FET amplifier stage can be conveniently assumed as infinite, as long as the operating frequency is low enough to neglect the capacitive impedances.
→ The feedback network is again three stage RC network having gain $|A| \geq 29$, $|\beta| = \frac{1}{29}$
→ The frequency of oscillations is, $f = \frac{1}{2\pi RC\sqrt{6}}$.

Advantages of RC phase shift oscillators

1) The circuit is simple to design.
2) Can produce output over audio frequency range.
3) produces sinusoidal output waveform.
4) It is a fixed frequency oscillator.

Derivation for frequency of oscillations of RC phase shift oscillator:





Applying KVL we get,

For loop 1, $-I_1R_c - \frac{1}{j\omega C}I_1 - I_1R + I_2R - h_{fe}I_bR_c = 0$.

But $R_c = KR$

$$\therefore I_1\left[(K+1)R + \frac{1}{j\omega C}\right] - I_2R = -h_{fe}I_bR_c \quad \text{— (1)}$$

For loop 2,

$$-\frac{1}{j\omega C}I_2 - I_2R - I_2R + I_1R + I_3R = 0.$$

$$\Rightarrow -I_1R + \left(2R + \frac{1}{j\omega C}\right)I_2 - I_3R = 0 \quad \text{— (2)}$$

For loop 3, $-I_3R - I_3\frac{1}{j\omega C} - I_3R + I_2R = 0$

$$\Rightarrow -I_2R + I_3\left(2R + \frac{1}{j\omega C}\right) = 0 \quad \text{— (3)}$$

using Cramer's Rule to solve for I_3,

$$\begin{array}{ccc} I_1 & I_2 & I_3 \end{array}$$
$$\begin{bmatrix} (K+1)R + \frac{1}{j\omega C} & -R & 0 \\ -R & 2R + \frac{1}{j\omega C} & -R \\ 0 & -R & 2R + \frac{1}{j\omega C} \end{bmatrix} \begin{bmatrix} I_1 \\ I_2 \\ I_3 \end{bmatrix} = \begin{bmatrix} -h_{fe}I_bKR \\ 0 \\ 0 \end{bmatrix}$$

$$D = \left[(K+1)R + \frac{1}{j\omega C}\right]\left[\left(2R + \frac{1}{j\omega C}\right)^2 - R^2\right] - (-R)\left[-R\left(2R + \frac{1}{j\omega C}\right)\right]$$

$$D = \left[(K+1)R + \frac{1}{j\omega C}\right]\left(2R + \frac{1}{j\omega C}\right)^2 - R^2\left[2R + \frac{1}{j\omega C}\right] - R^2\left[(K+1)R + \frac{1}{j\omega C}\right]$$

$$D_3 = \begin{vmatrix} (K+1)R+\frac{1}{j\omega C} & -R & -h_{fe} I_b KR \\ -R & 2R+\frac{1}{j\omega C} & 0 \\ 0 & -R & 0 \end{vmatrix}$$

$$D_3 = -R^2 (h_{fe} I_b KR) = -KR^3 h_{fe} I_b$$

$$I_3 = \frac{D_3}{D} = \frac{-KR^3 h_{fe} I_b}{\left[(K+1)R+\frac{1}{j\omega C}\right]\left(2R+\frac{1}{j\omega C}\right)^2 - R^2\left[2R+\frac{1}{j\omega C}\right] - R^2\left[(K+1)R+\frac{1}{j\omega C}\right]}$$

I_3 = output current of feedback circuit

I_b = Input current of amplifier

$I_c = h_{fe} I_b$ = Input current of the feedback circuit

$$\beta = \frac{\text{output of feedback circuit}}{\text{Input to feedback circuit}} = \frac{I_3}{h_{fe} I_b}$$

$$A = \frac{\text{output of amplifier circuit}}{\text{Input to amplifier circuit}} = \frac{I_c}{I_b} = \frac{h_{fe} I_b}{I_b} = h_{fe}$$

$$A\beta = \frac{I_3}{h_{fe} I_b} \times h_{fe} = \frac{I_3}{I_b}$$

$$\therefore A\beta = \frac{I_3}{I_b} = \frac{-KR^3 h_{fe}}{\left[(K+1)R+\frac{1}{j\omega C}\right]\left[2R+\frac{1}{j\omega C}\right]^2 - R^2\left[2R+\frac{1}{j\omega C}\right] - R^2\left[(K+1)R+\frac{1}{j\omega C}\right]}$$

$$A\beta = \frac{K h_{fe}}{[3K+1-5\alpha^2-K\alpha^2] + j[\alpha^3-4K\alpha-6\alpha]} \quad (4)$$

where $\alpha = \frac{1}{\omega CR}$

As per the Barkhausen criterion, $\angle A\beta = 0°$. The angle of numerator term Kh_{fe} of above equation is $0°$, hence to have angle of $A\beta$ term as $0°$, the imaginary part of the denominator term must be 0.

i.e $\alpha^3 - 4K\alpha - 6\alpha = 0$

$\alpha(\alpha^2 - 4K - 6) = 0$

$\Rightarrow \alpha = \sqrt{4K+6}$

$\Rightarrow \frac{1}{\omega CR} = \sqrt{4K+6}$

$\Rightarrow \omega = \frac{1}{CR\sqrt{4K+6}}$

$$\Rightarrow \boxed{f = \frac{1}{2\pi CR\sqrt{4K+6}}}$$

Consider,

$|A\beta| = 1$ and put $\alpha = \sqrt{4K+6}$ in eq^n (10)

$$(10) \Rightarrow |A\beta| = \left|\frac{Kh_{fe}}{3K+1-(4K+6)(5+K)}\right|$$

$$1 = \left|\frac{Kh_{fe}}{3K+1-20K-30-4K^2-6K}\right|$$

$$1 = \left|\frac{Kh_{fe}}{-4K^2-23K-29}\right|$$

$$\Rightarrow \frac{Kh_{fe}}{4K^2+23K+29} = 1.$$

$$\Rightarrow Kh_{fe} = 4K^2+23K+29$$

$$\Rightarrow \boxed{h_{fe} = 4K+23+\frac{29}{K}} \quad \left\{\text{where } K = \frac{R_c}{R}\right\}$$

This must be the value of h_{fe} for the oscillations.

Minimum Value of h_{fe} for the oscillations :

To get the minimum value of h_{fe},

$$\frac{dh_{fe}}{dK} = 0$$

$$\therefore \quad h_{fe} = 4K + 23 + \frac{29}{K}$$

$$\Rightarrow \quad \frac{dh_{fe}}{dK} = 4 + 0 - \frac{29}{K^2}$$

$$0 = 4 - \frac{29}{K^2}$$

$$\Rightarrow \quad \frac{29}{K^2} = 4 \quad \Rightarrow \quad K = \sqrt{\frac{29}{4}} = 2.6925 \text{ for minimum } h_{fe}.$$

$$\therefore \quad (h_{fe})_{min} = 4K + 23 + \frac{29}{K}$$

$$= 4(2.6925) + 23 + \frac{29}{2.6925}$$

$$(h_{fe})_{min} = 44.54$$

Thus for the circuit to oscillate we must select the transistor whose $(h_{fe})_{min}$ should be greater than 44.54

Prob(1): Find the capacitor 'C' and h_{fe} for the transistor to provide a resonating frequency of 10KHz of a transistorised RC phase shift oscillator.

$R_C = 20K\Omega$, $R = 7.1K\Omega$.

Soln: $K = \frac{R_c}{R} = \frac{20K}{7.1K} = 2.817$

$$f = \frac{1}{2\pi CR\sqrt{6+4K}}$$

$$10\times10^3 = \frac{1}{2\pi C\times7.1\times10^3\times\sqrt{6+4\times2.817}}$$

$$\Rightarrow C = 539.44\,pF$$

$$h_{fe} \geq 4K+23+\frac{29}{K}$$

$$\geq 4\times2.817+23+\frac{29}{2.817}$$

$$h_{fe} \geq 44.56$$

Prob(2): A RC phase shift oscillator generates 5KHz sine wave with $C = 1nF$ and $h_{fe} = 150$. Find 'R' and R_c.

Soln: $h_{fe} = 4K+23+\frac{29}{K}$

$$150 = 4K+23+\frac{29}{K}$$

$$\Rightarrow 4K^2 - 127K + 29 = 0$$

$$K = 31.52,\ 0.23$$

{ let $=0.23$ $\because K = \frac{R_c}{R}$ & $R >> R_c$ }

$$f = \frac{1}{2\pi CR\sqrt{6+4K}}$$

$$5\times10^3 = \frac{1}{2\pi\times10^{-9}\times R\sqrt{6+4\times0.23}} \Rightarrow R = 12.1K\Omega$$

$K = \frac{R_c}{R} \Rightarrow R_c = KR = 0.23\times12.1\times10^3 = 2.783\,K\Omega$

prob(3): A FET phase shift oscillator has $g_m = 5m$ mhos, $r_d = 50K\Omega$, $R = 100K\Omega$ and $C = 64.79\,pF$. Find the frequency of oscillations and R_D.

soln.

$$f = \frac{1}{2\pi\sqrt{6}\,CR} = \frac{1}{2\pi \times \sqrt{6} \times 64.79 \times 10^{-12} \times 100 \times 10^{3}} = 10.03\,KHz.$$

$|A| = g_m R_L$ but $|A| \geq 29$.

$\therefore\ g_m R_L \geq 29$

$$\Rightarrow R_L \geq \frac{29}{g_m} = \frac{29}{5 \times 10^{-3}} = 5.8\,K\Omega$$

Let $R_L = 6K\Omega$.

But $R_L = R_D \| r_d = \dfrac{R_D r_d}{R_D + r_d}$

$$\Rightarrow\quad 6 \times 10^{3} = \frac{R_D \times \cancel{50} \times 10^{3}}{R_D + 50 \times 10^{3}}$$

$$\Rightarrow\quad R_D = 6.818\,K\Omega$$

prob(4): A FET phase shift oscillator having $g_m = 5000\,\mu$ mho, $r_d = 40\,K\Omega$, $R = 9.7K\Omega$. Find C and R_D to have frequency of oscillations as $5KHz$.

soln.

$$f = \frac{1}{2\pi\sqrt{6}\,RC} \Rightarrow 5 \times 10^{3} = \frac{1}{2\pi \times \sqrt{6} \times 9.7 \times 10^{3} \times C} \Rightarrow C = 1.34\,nF.$$

$$|A| = g_m R_L \geq 29 \Rightarrow R_L \geq \frac{29}{g_m} = \frac{29}{5000 \times 10^{-6}} = 5.8\,K\Omega$$

let $R_L = 6K\Omega$

But $R_L = R_D \| r_d = \dfrac{R_D \times r_d}{R_D + r_d}$

$$\Rightarrow\quad 6 \times 10^{3} = \frac{40 \times 10^{3} \times R_D}{R_D + 40 \times 10^{3}}$$

$$\Rightarrow\quad R_D = 7.06\,K\Omega$$

Prob(5): Design a FET phase shift oscillator to operate at a frequency of 2KHz. $\mu = 50$, $r_d = 5K\Omega$, $C = 1nF$. Also find R_D.

Sol^n:
$$f = \frac{1}{2\pi\sqrt{6} \times RC} \Rightarrow 2 \times 10^3 = \frac{1}{2\pi \times \sqrt{6} \times R \times 10^{-9}}$$

$$\Rightarrow R = 32.5 K\Omega$$

$$\boxed{\mu = g_m r_d} \Rightarrow 50 = g_m \times 5 \times 10^3 \Rightarrow g_m = 0.01.$$

But $|A| = g_m R_L \geq 29 \Rightarrow R_L \geq \frac{29}{g_m} = \frac{29}{0.01} = 2.9 K\Omega$

$$R_L = R_D || r_d = \frac{R_D \times r_d}{R_D + r_d}$$

$$\Rightarrow 2.9 \times 10^3 = \frac{R_D \times 5 \times 10^3}{R_D + 5 \times 10^3} \Rightarrow R_D = 6.9 K\Omega$$

Disadvantages of RC phase shift oscillator:

→ By changing the values of R and C, the frequency of the oscillator can be changed. But the values of R and C of all three sections must be changed simultaneously to satisfy the oscillating conditions. But this is practically impossible. Hence the phase shift oscillator is considered as a fixed frequency oscillator, for all practical purposes.

→ The frequency stability is poor due to the changes in the values of various components, due to effect of temperature, aging etc.

Wein Bridge oscillator:

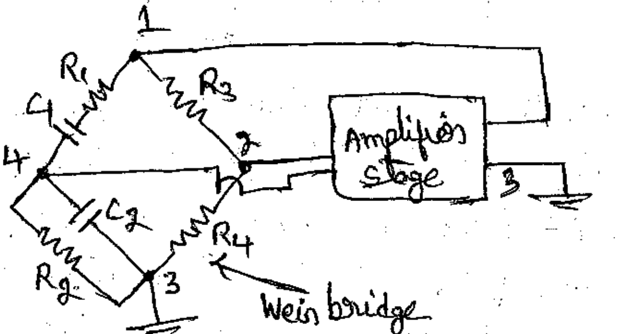


Fig: Basic Circuit of Wein Bridge oscillator

→ Generally in an oscillator amplifier stage introduces 180° phase shift and feedback network introduces additional 180° phase shift, to obtain a phase shift of 360° around a loop. This is required condition for any oscillator.

→ But Wein Bridge oscillator uses a non-inverting amplifier and hence does not provide any phase shift during amplifier stage. As total phase shift required is 0° or 360°, in Wein Bridge type no phase shift is necessary through feedback. Thus the total phase shift around a loop is 0°.

→ A basic Wein bridge used in this oscillator and amplifier stage is as shown in fig.

→ The output of the amplifier is applied between the terminals 1 and 3, which is the input to the feedback network. While the amplifier input is supplied from the diagonal terminals 2 and 4, which is the output from the feedback network. Thus amplifier supplied its own input through the Wein bridge as a feedback network.

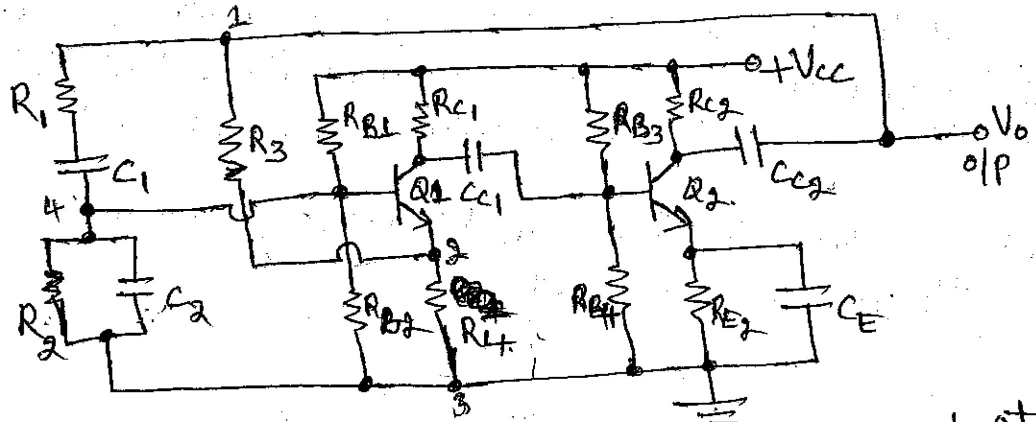
→ The two arms of the bridge, namely R_1, C_1 in series and R_2, C_2 in parallel are called frequency sensitive arms. This is because the components of these two arms decide the frequency of the oscillator. The input to the feedback network is between 1 and 3 while output of the feedback network is between 2 and 4. Such a feedback network is called Lead-lag network. This is because at very low frequencies it acts like a lead while at very high frequencies it acts like lag network.

→ The frequency of oscillations is given as, $f = \frac{1}{2\pi\sqrt{R_1 R_2 C_1 C_2}}$

→ By varying the two capacitor values simultaneously by mounting them on the common shaft, different frequency ranges can be provided.

→ If the bridge is not balanced, then the oscillations will not take place as $|A\beta| \geq 1$ will not be satisfied.

Wein Bridge Oscillator using BJT:



→ In this circuit, two stage CE amplifier is used. Each stage contributes 180° phase shift hence the total phase shift due to the amplifier stage becomes 360° i.e 0° which is necessary as per the oscillator conditions.

→ The bridge consists of R and C in series, R and C in parallel, R_3 and R_4. The feedback is applied from the collector of Q_2 through the coupling capacitor, to the bridge circuit. The resistance R_4 serves the dual purpose of emitter resist of the transistor Q_1 and also the element of the Wein bridge.

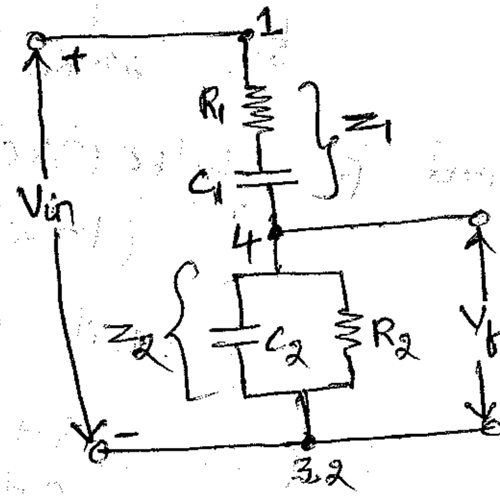
→ The two stage amplifier provides a gain much more than 3 and it is necessar to reduce it. To reduce the gain, the negative feedback is used without bypassing the resistance R_4.

→ The negative feedback can accomplish the gain stability and can control the output magnitude. The negative feedback also reduces the distortion and therefore output obtained is a pure sinusoidal in nature.

→ The amplitude stability can be improved using a nonlinear resistor for R_4. Due to this, the loop gain depends on the amplitude of the oscillations. Increase in the amplitude of the oscillations, increases the current through non-linear resistan which results into an increase in the value of non-linear resistance R_4.

→ When this value increases, a greater amount of negative feedback is applied. This reduces the loop gain. And hence signal amplitude gets reduced and controlle

Derivation for the frequency of oscillations for Wein Bridge oscillator:

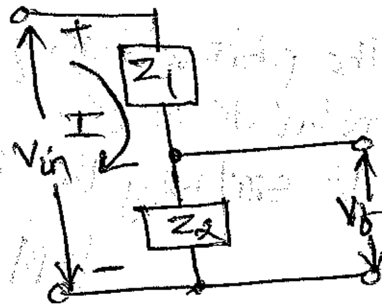


$$Z_1 = R_1 + \frac{1}{j\omega C_1} = \frac{1 + j\omega R_1 C_1}{j\omega C_1}$$

$$Z_2 = R_2 \,||\, \frac{1}{j\omega C_2} = \frac{R_2 \times \frac{1}{j\omega C_2}}{R_2 + \frac{1}{j\omega C_2}} = \frac{R_2}{1 + j\omega R_2 C_2}$$

$$I = \frac{V_{in}}{Z_1 + Z_2}$$

and $$V_f = I Z_2 = \frac{V_{in} Z_2}{Z_1 + Z_2}$$



$$\Rightarrow \quad \frac{V_f}{V_{in}} = \beta = \frac{Z_2}{Z_1 + Z_2}$$

$$\therefore \beta = \frac{R_2 / (1 + j\omega R_2 C_2)}{\frac{1 + j\omega R_1 C_1}{j\omega C_1} + \frac{R_2}{1 + j\omega R_2 C_2}}$$

$$\beta = \frac{\omega^2 C_1 R_2 \left[R_1 C_1 + R_2 C_2 + R_2 C_1\right] + j\omega C_1 R_2 \left[1 - \omega^2 R_1 R_2 C_1 C_2\right]}{(1 - \omega^2 R_1 R_2 C_1 C_2)^2 + \omega^2 (R_1 C_1 + R_2 C_2 + R_2 C_1)^2}$$

To have zero phase shift of the feedback network, its imaginary part must be zero.

$$\therefore \quad 1 - \omega^2 R_1 R_2 C_1 C_2 = 0$$

$$\Rightarrow \quad \omega^2 = \frac{1}{R_1 R_2 C_1 C_2}$$

$$\Rightarrow \quad \boxed{f = \frac{1}{2\pi \sqrt{R_1 R_2 C_1 C_2}}}$$

If $R_1 = R_2 = R$ and $C_1 = C_2 = C$ then,

$$f = \frac{1}{2\pi RC} \Rightarrow \omega = \frac{1}{RC}$$

and $$\beta = \frac{\omega^2 RC(3RC) + j\omega RC(1-\omega^2R^2C^2)}{(1-\omega^2R^2C^2) + \omega^2(3RC)^2}$$

But $\omega = \frac{1}{RC}$

$$\therefore \beta = \frac{3+0}{0+9} = \frac{3}{9} = \frac{1}{3}$$

The positive sign of 'β' indicates that the phase shift by the feedback network is $0°$.

To satisfy the Barkhausen criterion for the sustained oscillations,

$$|A\beta| \geq 1$$

$$\Rightarrow |A| \geq \frac{1}{|\beta|} = \frac{1}{1/3} = 3 \qquad \boxed{\therefore |A| \geq 3}$$

Hence the gain of the Wein Bridge oscillator is atleast equal to '3' for oscillations to occur.

If $R_1 \neq R_2$ and $C_1 \neq C_2$ then $f = \frac{1}{2\pi\sqrt{R_1C_1R_2C_2}}$

$$\Rightarrow \omega = \frac{1}{\sqrt{R_1R_2C_1C_2}}$$

$$\Rightarrow \beta = \frac{C_1R_2}{R_1C_1 + R_2C_2 + R_2C_1}$$

But $|A\beta| \geq 1$

$$\Rightarrow |A| \geq \frac{1}{|\beta|}$$

$$\Rightarrow |A| \geq \frac{R_1C_1 + R_2C_2 + R_2C_1}{C_1R_2}$$

prob(1): A Wien Bridge oscillator has a frequency of 500 Hz. if the value of C is 100 pF find the value of R.

Soln:

$$f = \frac{1}{2\pi RC} \Rightarrow R = \frac{1}{2\pi f C} = \frac{1}{2\pi \times 500 \times 100 \times 10^{-12}}$$

$$R = 3.183 M\Omega$$

prob(2): In a Wien-Bridge oscillator, if the value of R is 100 K-Ω and the frequency of oscillation is 10 KHz, find the value of capacitor 'C'.

Soln:

$$f = \frac{1}{2\pi RC} \Rightarrow C = \frac{1}{2\pi f R} = \frac{1}{2\pi \times 10 \times 10^3 \times 100 \times 10^3} = 159 PF.$$

prob(3): The frequency sensitive arms of the Wien Bridge oscillator uses $C_1 = C_2 = 0.001\ \mu F$ and $R_1 = 10 K\Omega$ while R_2 is kept variable. The frequency is to be varied from 10 KHz to 50 KHz by varying R_2. Find the minimum and maximum values of R_2.

Soln:

$$f = \frac{1}{2\pi\sqrt{R_1 R_2 C_1 C_2}} = \frac{1}{2\pi C \sqrt{R_1 R_2}}$$

For $f = 10 KHz$,

$$10 \times 10^3 = \frac{1}{2\pi \times \sqrt{10 \times 10^3 \times R_2 \times (0.001 \times 10^{-6})^2}}$$

$$\Rightarrow R_2 = 25.33 K\Omega$$

For $f = 50 KHz$,

$$50 \times 10^3 = \frac{1}{2\pi \times \sqrt{10 \times 10^3 \times R_2 \times (0.001 \times 10^{-6})^2}}$$

$$\Longrightarrow R_2 = 1.013 K\Omega$$

so minimum value of R_2 is $1.013 K\Omega$ while the maximum value of R_2 is $25.33 K\Omega$.

Problem: A [illegible] oscillator has frequency of [illegible]. If the value of C is [illegible] find the value of L.

Soln: $f = \frac{1}{2\pi\sqrt{LC}}$ [illegible]

$L =$ [illegible]

Problem: In a [illegible] oscillator, if the value of C is [illegible] and the frequency of oscillation is [illegible], find the value of [illegible]

Soln: [illegible]

Problem: The frequency [illegible] in the [illegible] oscillator [illegible]

[illegible]

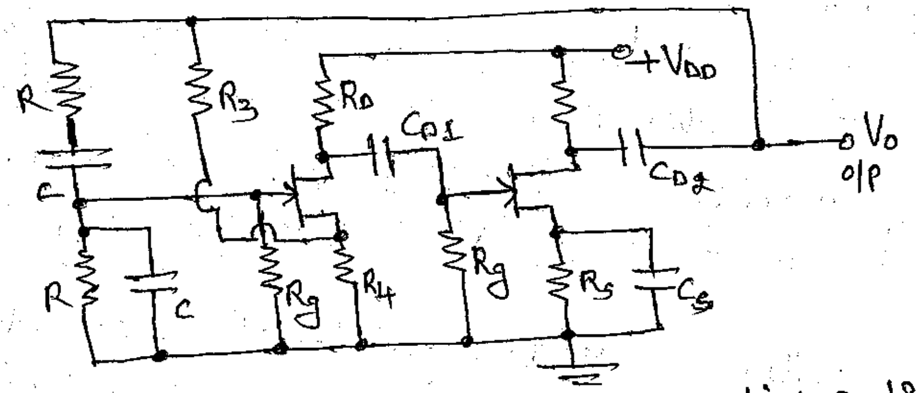
[illegible] maximum value of [illegible]

Soln: [illegible]

[illegible]

[illegible] maximum value of [illegible]

Wein Bridge oscillator using FET:



→ A single stage FET amplifier gives a phase shift of 180° and it is required to have 360° phase shift from amplifier stage, the two stages of FET amplifier is the feature of the Wein bridge oscillator using FET.

→ The RC series and parallel combination forms the frequency sensitive arms of the Wein bridge. The resistances R_3 and R_4 form the part of the feedback path. The unbypassed source resistance R_4 provides the negative feedback required for gain stabilization.

→ The amplifier gain is the product of the gains of the two stages. The operation of the circuit is similar to wein bridge oscillator using BJT.

Comparision of RC phase shift and Wein Bridge oscillators:

RC phase shift oscillator	Wein Bridge oscillator
1) Used for low frequency range.	1) Used for low frequency range.
2) Feedback network is RC network with three RC sections.	2) The feedback network is lead-lag network called as Wein bridge circuit.
3) The feedback network introduces 180° phase shift	3) Feedback n/w does not introduce any phase shift
4) Amplifier circuit introduces 180° phase shift.	4) Amplifier circuit does not introduce any phase shift.
5) $f = \frac{1}{2\pi RC\sqrt{6}}$	5) $f = \frac{1}{2\pi\sqrt{R_1C_1R_2C_2}}$
6) Amplifier gain condition is $\lvert A\rvert \geq 29$.	6) Amplifier gain condition is $\lvert A\rvert \geq 3$.
7) Frequency variation is difficult.	7) Frequency variation can be achieved

Frequency stability of oscillator:

→ For an oscillator, the frequency of the oscillations must remain constant. The analysis of the dependence of the oscillating frequency on the various factors like stray capacitance, temperature etc. is called as the frequency stability analysis.

→ The measure of ability of an oscillator to maintain the desired frequency as precisely as possible for as long a time as possible is called frequency stability of an oscillator.

→ In a transistorised Colpitts oscillator or Hartley oscillator, the base-collector junction is reverse biased and there exists an internal capacitance which is dominant at high frequencies. This capacitance affects the value of capacitance in the tank circuit and hence the oscillating frequency.

→ Similarly the transistor parameters are temperature sensitive. Hence as temperature changes, the oscillating frequency also changes and no longer remains stable. Hence practically the circuits cannot provide stable frequency.

→ In general following are the factors which affect the frequency stability of an oscillator,

1) Due to the changes in temperature, the values of the components of tank circuit get affected. So changes in the values of inductors and capacitors due to the changes in the temperature is the main cause due to which frequency does not remain stable.
2) Due to the changes in temperature, the parameters of the active device used like BJT, FET get affected which inturn affect the frequency.
3) The variation in the power supply is another factor affecting the frequency.
4) The changes in the atmospheric conditions, aging and unstable transistor parameters affect the frequency.
5) The changes in the load connected, affect the effective resistance of the tank circuit.
6) The capacitive effect in transistor and stray capacitances, affect the capacitance of the tank circuit and hence the frequency.

→ The variation of frequency with temperature is given by the factor denoted as S

$$S_{\omega_r,T} = \frac{\Delta\omega/\omega_r}{\Delta T/T_r}$$ parts per million per $^{\circ}C$

where, ω_r = desired frequency
T_r = operating ~~frequency~~ Temp
$\Delta\omega$ = change in frequency
ΔT = change in temperature

→ The frequency stability is defined as,

$S_\omega = \frac{d\theta}{d\omega}$ where, $d\theta$ = phase shift introduced for a small frequency change desired frequency.

→ Larger the value of $d\theta/d\omega$, more stable is the oscillator.

→ The frequency stability of an oscillator can be improved by the following modifications,

1) Enclosing the circuit in a constant temperature chamber.
2) Maintaining constant voltage by using the zener diodes.
3) The load affect is reduced by coupling the oscillator to the load loosely or wit the help of a circuit having high input impedance and low output impedance.

Crystal oscillators:

→ The crystals are either naturally occuring or synthetically manufactured, exhibiting t piezoelectric effect. → The piezoelectric effect means under the influence of the mechanic pressure, the voltage gets generated across the opposite faces of the crystal. If the mechanical force is applied in such a way to force the crystal to vibrate, the a.c volt gets generated across it. Conversely, if the crystal is subjected to a.c voltage, it vibrates causing mechanical distortion in the crystal shape.

→ Every crystal has its own resonating frequency depending on its cut. So under th influence of mechanical vibrations, the crystal generates an electrical signal of ve constant frequency.

→ The crystal has a greater stability in holding the constant frequency. A crystal oscillator is basically a tuned circuit oscillator using a piezoelectric crystal as i resonant tank circuit.

→ The crystal oscillators are preferred when greater frequency stability is requi Hence the crystals are used in watches, communication transmitters and receivers

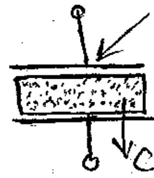
→ The main substances exhibiting the piezoelectric effect are quartz, Rochelle sal and Tourmaline. Rochelle salts have the greatest piezoelectric activity. For a given a.c voltage, they vibrate more than quartz or tourmaline. Hence these are preferred in making microphones associated with portable tape recorders, headsets, loudspeakers etc.

→ Rochelle salt is mechanically weakest of the three and break very easily.

→ Tourmaline shows least piezoelectric effect but mechanically strongest a Tourmaline is the most expensive and hence its use is rare.

→ In practice Quartz is a compromise between the piezoelectric activity of Rochelle salts and the strength of the tourmaline.

→ Quartz is inexpensive and easily available in nature and hence very commonl
used in the crystal oscillators.
→ Quartz is widely used for RF oscillators and the filters.
→ The natural shape of a quartz crystal is a hexagonal prism.
But for its practical use, it is cut to the rectangular slab.
This slab is then mounted between the two metal plates.
→ The symbolic representation of such a practical crystal is
shown in figure. The metal plates are called holding plates, as they hold
the crystal slab in between them.



AC Equivalent Circuit:

→ When the crystal is not vibrating, it is equivalent to a
capacitor due to the mechanical mounting of the crystal. Such a
capacitance existing due to the two metal plates separated by
a dielectric like crystal slab is called mounting capacitance
denoted as C_M.

→ When the crystal is vibrating, there are internal frictional
losses which are denoted by a resistance R. While the mass
of the crystal, which is indication of its inertia is represented
by an inductance 'L'.

→ In vibrating condition, it is having some stiffness, which is represented by a
capacitor 'C'. The mounting capacitance is a shunt capacitance. And hence the over
equivalent circuit of a crystal can be as shown in figure above.

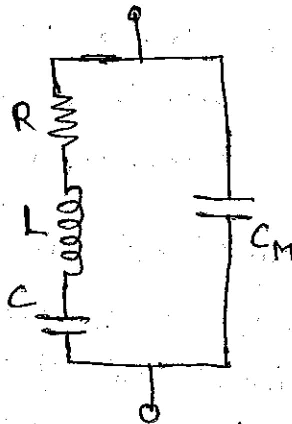


Fig: AC equivalent ckt of crysta

→ RLC forms a resonating circuit. The expression for the resonating frequen
is,

$$f_r = \frac{1}{2\pi\sqrt{LC}} \cdot \sqrt{\frac{Q^2}{1+Q^2}}$$

where, Q = quality factor of crystal $= \frac{\omega L}{R}$

→ The Q factor of crystal is very high, typically 20,000. Value of 'Q' upto 10^6 al
can be achieved. Hence $\sqrt{\frac{Q^2}{1+Q^2}}$ factor approaches to unit and we get the resonat
frequency as,

$$f_r = \frac{1}{2\pi\sqrt{LC}}$$

→ The crystal frequency is infact inversely proportional to the thickness of the crys

$$f \propto \frac{1}{t} \quad \text{where } t = \text{thickness}.$$

→ So we have very high frequencies, thickness of the crystal should be very small. But it makes the crystal mechanically weak and hence it may get damaged, under the vibrations. Hence practically crystal oscillators are used upto 200 or 300 KHz only.

→ The crystal has two resonating frequencies, series resonant frequency and parallel resonant frequency.

→ one resonant condition occurs when the reactances of series RLC leg are equal i.e $X_L = X_C$. This is nothing but the series resonance. The impedance offered by this branch, under resonant condition is minimum which is resistance R. The series resonance frequency is same as the resonating frequency given by,

$$f_s = \frac{1}{2\pi\sqrt{LC}}$$

→ The other resonant condition occurs when the reactances of series resonant leg equals the reactance of the mounting capacitor C_M. This is parallel resonance or antiresonance condition.
under this condition the impedance offered by the crystal to the external circuit is maximum.
under parallel resonance, the equivalent capacitance is, $C_{eq} = \frac{C_M \cdot C}{C_M + C}$
Hence parallel resonating frequency is given by, $f_P = \frac{1}{2\pi\sqrt{LC_{eq}}}$.

Crystal stability:

→ The frequency of crystal tends to change slightly with time due to temperature, aging etc.

(i) Temperature stability:
It is defined as the change in the frequency per degree change in temperature. This is Hz/MHz/°C. For 1°C change in the temperature, the frequency changes by 10 to 12 Hz in MHz. This is negligibly small. So for all practical purposes it is treated to be constant. But if this much change is also not acceptable then the crystal is kept in box where temperature is maintained constant, called constant temperature oven or constant temperature box.

(ii) long term stability: It is basically due to aging of the crystal material. Aging rates are 2×10^{-8} per year, for a quartz crystal. This is also negligibly small.

(iii) short term stability: In a quartz crystal, the frequency drift with time is typically less than 1 part in 10^6 i.e 0.0001% per day. This is also very small.

→ overall crystal has good frequency stability. Hence it is used in computers, counters, basic timing devices in electronic wrist watches, etc.

Pierce crystal oscillator:

→ The Colpitts oscillator can be modified by using the crystal to behave as an inductor. This circuit is called pierce crystal oscillator. The crystal behaves as an inductor for a frequency slightly higher than the series resonance frequency of ... in the tank circuit along with an inductor.

→ The two capacitors C_1, C_2 required in the tank circuit along with an inductor are used, as they are used in Colpitts oscillator circuit.

→ As only inductor gets replaced by the crystal, which behaves as an inductor, the basic working principle of pierce crystal oscillator is same as that of Colpitts oscillator.

→ The resistances R_1, R_2, R_E provide d.c bias while the capacitor C_E is emitter bypass capacitor. RFC (Radio frequency choke) provides isolation between a.c and d.c operation. C_{c1} and C_{c2} are coupling capacitors.

→ The resulting circuit frequency is set by the series resonant frequency of the crystal, change in the supply voltages, temperature, transistor parameters have no effect on the circuit operating conditions and hence good frequency stability is obtained.

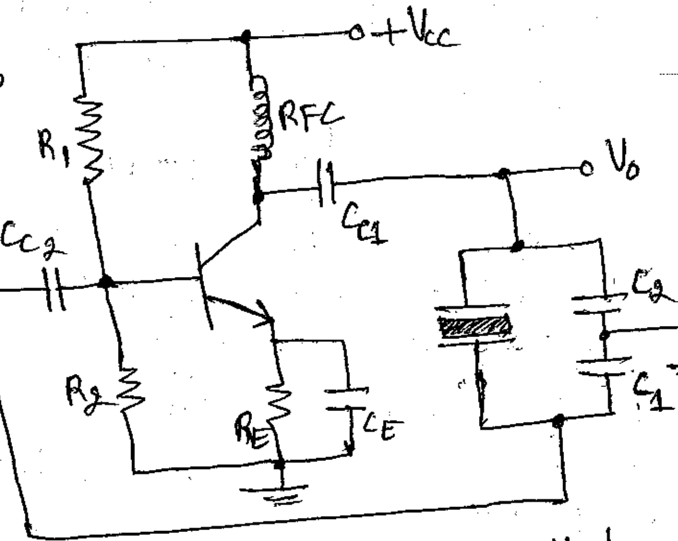
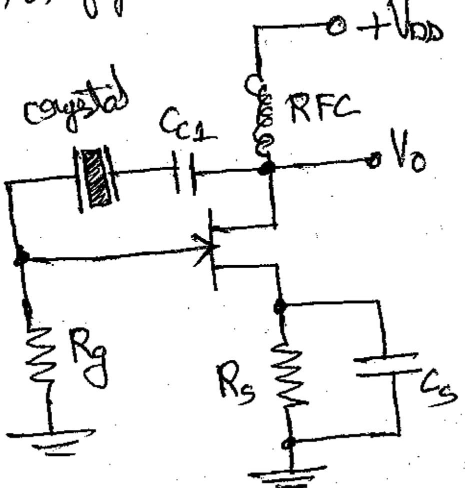
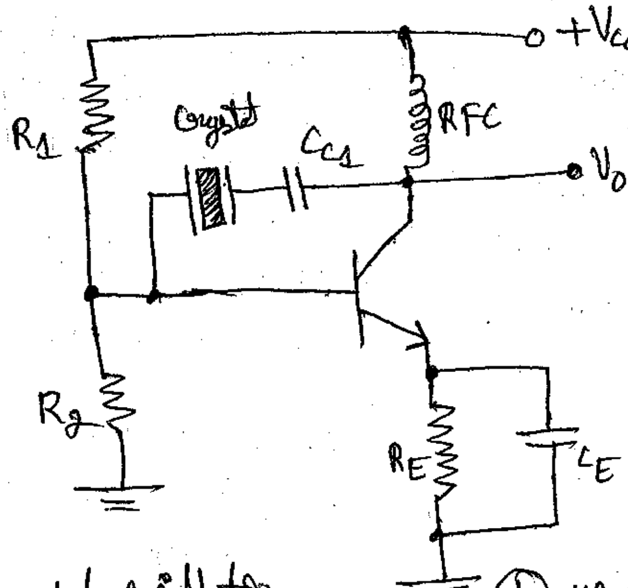


Fig: pierce crystal oscillator.

→ The oscillatory circuit can be modified by using the internal capacitors of the transistor used instead of C_1 and C_2. The separate capacitors C_1 and C_2 are not required in such circuit. Such circuits using FET and BJT are as shown in figure below.



(a) using FET



(b) using BJT

Fig: pierce crystal oscillator.

Miller crystal capacitor:

→ Similar to modifications in Colpitts oscillator, the Hartley oscillator circuit can be modified, to get Miller crystal oscillator.

→ In Hartley oscillator circuit, two inductors and one capacitor is required in the tank circuit.

→ one inductor is replaced by the crystal which acts as an inductor for the frequencies slightly greater than the series resonant frequency.

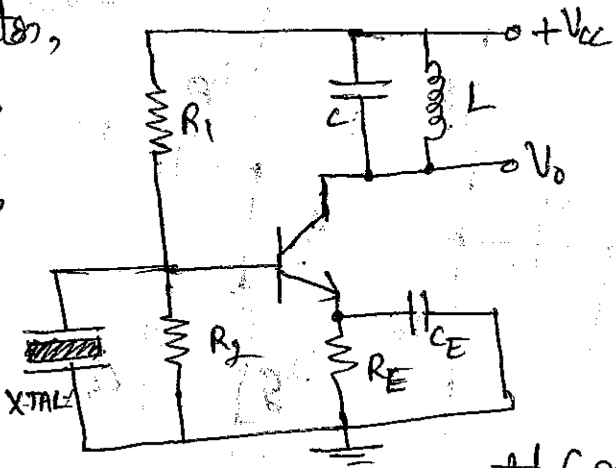


Fig: Miller crystal capacitor

→ The transistorised Miller crystal oscillator circuit is as shown in figure.

→ The tuned circuit of L_1 and C is offtuned to behave as an inductor i.e L_1. The crystal behaves as other inductance L_2 between base and ground.

→ The internal capacitance of the transistor acts as a capacitor required to fulfil the elements of the tank circuit. The crystal decides the operating frequency of the oscillator.

Oscillators using FET:

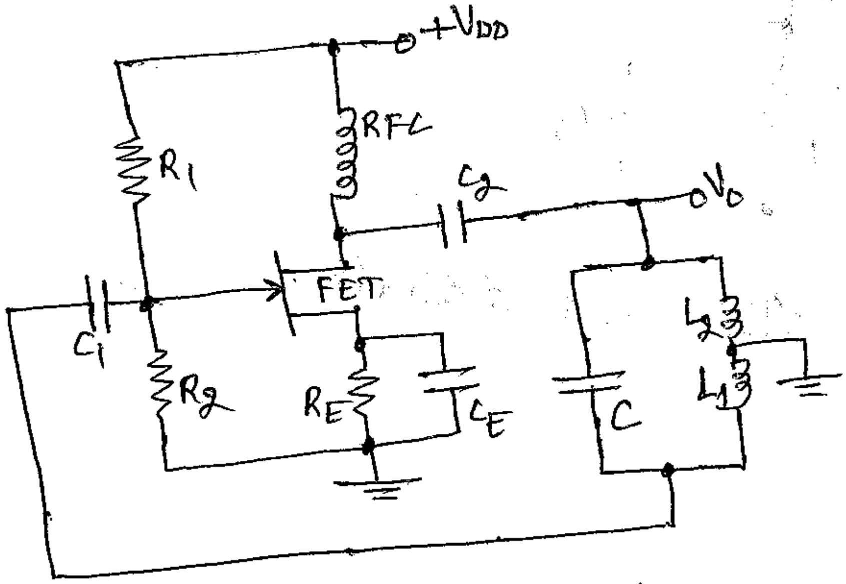


Fig: FET Hartley oscillator.

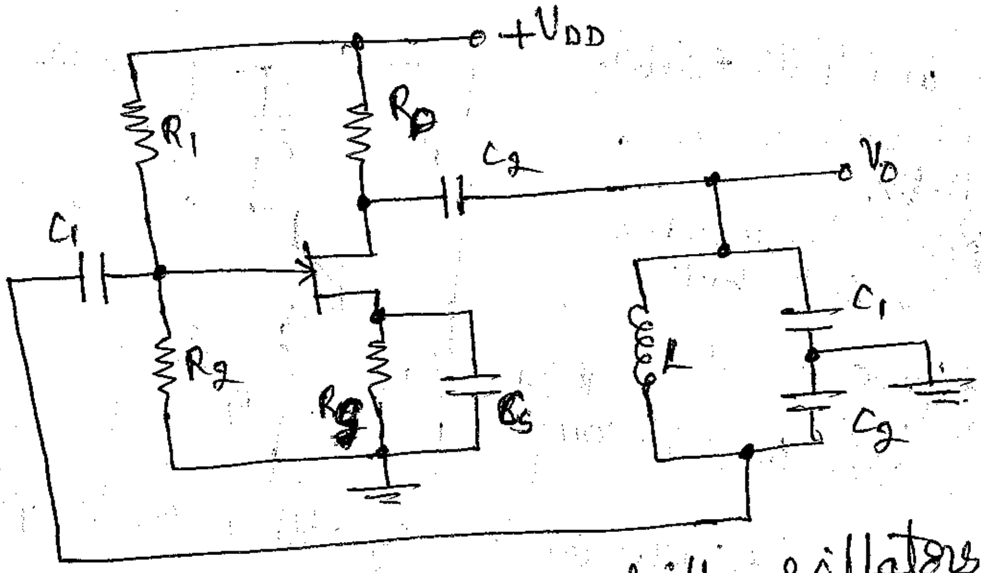


Fig: FET Colpitts oscillators.

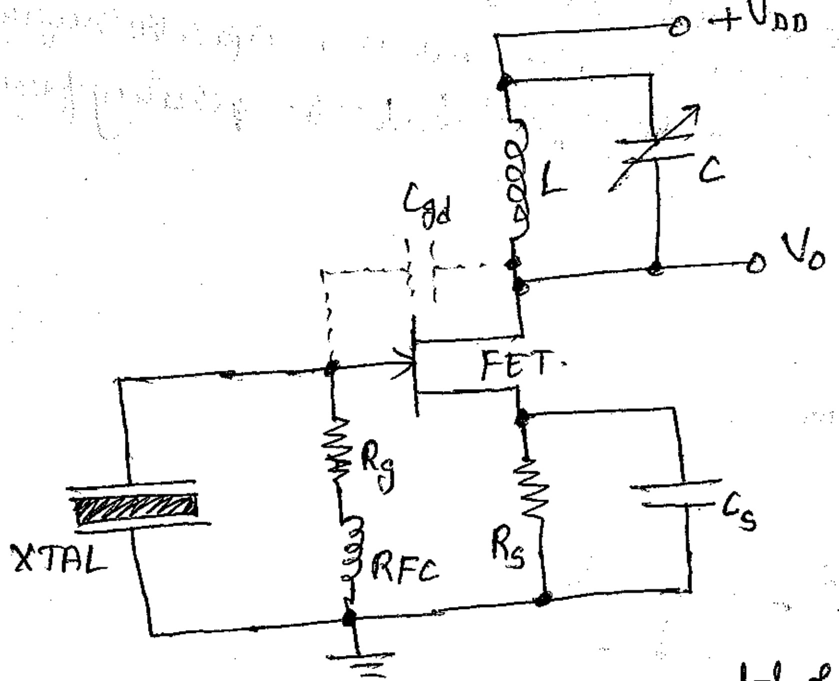


Fig: FET Miller crystal oscillator.

problem: In a RC phase shift oscillator, the phase shift network uses the resistance each of 4.7KΩ and the capacitors each of 0.47 μF. Find the frequency of oscillations.

Solⁿ: $R = 4.7 K\Omega$, $C = 0.47 \mu F$.

$$f = \frac{1}{2\pi RC\sqrt{6}} = \frac{1}{2\pi \times 4.7\times10^{3}\times 0.47\times10^{-6}\times\sqrt{6}} = 29.413 Hz.$$

problem: For the RC phase shift oscillator, the feedback network uses $R = 6K\Omega$ and $C = 1500$ The transistorised amplifier used, has a collector resistance of 18KΩ. Calculate the frequency of oscillations.

Solⁿ: $R = 6K\Omega$, $C = 1500pF$, $R_C = 18K\Omega$.

$$K = R_C/R = 18K/6K = 3.$$

$$\therefore f = \frac{1}{2\pi RC\sqrt{6+4K}} = \frac{1}{2\pi\times 6\times10^{3}\times 1500\times10^{-12}\times\sqrt{6+4\times3}} = 4.168 KHz.$$

problems:

The frequency sensitive arms of the Wein bridge oscillator uses $C_1 = C_2 = 0.001 \mu F$ and $R_1 = 10K\Omega$ while R_2 is kept variable. The frequency is to be varied from 10KHz to 50KHz, by varying R_2. Find the minimum and maximum values of R_2

Solⁿ: $R_1 = 10K\Omega$, $C_1 = C_2 = 0.001 \mu F$.

$$f = \frac{1}{2\pi\sqrt{R_1 R_2 C_1 C_2}}$$

$$\Rightarrow 10K = \frac{1}{2\pi\sqrt{10\times10^{3}\times R_2\times(0.001\times10^{-6})^2}}$$

$$\Rightarrow R_2 = 25.33 K\Omega$$

$$f = \frac{1}{2\pi\sqrt{R_1 R_2 C_1 C_2}}$$

$$\Rightarrow 50\times10^{3} = \frac{1}{2\pi\sqrt{10\times10^{3}\times R_2\times(0.001\times10^{-6})^2}}$$

$$\Rightarrow R_2 = 1.013 K\Omega$$

So minimum value of R_2 is $1.013K\Omega$ and maximum value of R_2 is $25.33 K\Omega$

problem: Find the frequency of oscillations of a transistorised colpitts oscillator having $C_1 = 150\,pF$, $C_2 = 1.5\,nF$ and $L = 50\,\mu H$.

Soln:
$$C_{eq} = \frac{C_1 C_2}{C_1 + C_2} = \frac{150\times10^{-12} \times 1.5\times10^{-9}}{150\times10^{-12} + 1.5\times10^{-9}} = 136.363\,pF$$

$$f = \frac{1}{2\pi\sqrt{L C_{eq}}} = \frac{1}{2\pi\sqrt{50\times10^{-6} \times 136.363\times10^{-12}}} = 1.927\,MHz.$$

problem: In a colpitts oscillator, $C_1 = C_2 = C$ and $L = 100\,\mu H$. The frequency of oscillations is $500\,KHz$. Determine value of C.

Soln:
$$f = \frac{1}{2\pi\sqrt{L C_{eq}}}$$

$$\Rightarrow 500\times10^{3} = \frac{1}{2\pi\sqrt{100\times10^{-6}\times C_{eq}}} \Rightarrow C_{eq} = 1.0132\times10^{-9}\,F.$$

$$\text{But } C_{eq} = \frac{C_1 C_2}{C_1 + C_2} = \frac{C\cdot C}{C+C} = \frac{C^2}{2C} = \frac{C}{2}.$$

$$\Rightarrow 1.0132\times10^{-9} = \frac{C}{2} \Rightarrow C = 2.026\times10^{-9}\,F = 2.026\,nF.$$

problem: In Hartley oscillator, calculate L_2 if $L_1 = 15\,mH$, $C = 50\,pF$, mutual inductance of $5\,\mu H$ and the frequency of oscillations is $168\,KHz$. $L_2 = ?$

Soln: $L_1 = 15\,mH$, $C = 50\,pF$, $M = 5\,\mu H$, $f = 168\,KHz$.

$$f = \frac{1}{2\pi\sqrt{L_{eq}\cdot C}}$$

$$\Rightarrow 168\times10^{3} = \frac{1}{2\pi\sqrt{L_{eq}\times 50\times10^{-12}}} \Rightarrow L_{eq} = 17.9494\,mH.$$

But, $L_{eq} = L_1 + L_2 + 2M$

$$\Rightarrow 17.9494 = 15\times10^{-3} + L_2 + 2\times5\times10^{-6}$$

$$\Rightarrow L_2 = 2.9394\,mH.$$

problem: In a transistorised Hartley oscillator the two inductances are 2mH and 20μH while the frequency is to be changed from 950KHz to 2050KHz. Calculate the range over which the capacitor is to be varied.

Soln: $L_{eq} = L_1 + L_2 = 2\times10^{-3} + 20\times10^{-6} = 2.02\,mH.$

$$f = \frac{1}{2\pi\sqrt{L_{eq}\cdot C}} \qquad\qquad f = \frac{1}{2\pi\sqrt{L_{eq}\cdot C}}$$

$$\Rightarrow 2050\times10^{3} = \frac{1}{2\pi\times\sqrt{C\times2.02\times10^{-3}}} \qquad \Rightarrow 950\times10^{3} = \frac{1}{2\pi\times\sqrt{C\times2.02\times10^{-3}}}$$

$$\Rightarrow C = 2.98\,PF \qquad\qquad \Rightarrow C = 13.89\,PF.$$

Here 'C' must be varied from 2.98PF to 13.89PF to get the required frequency variation.

problem: A crystal $L = 0.4H$, $C = 0.085\,PF$ and $C_M = 1PF$ with $R = 5K\Omega$.
Find, (i) series resonant frequency (ii) parallel resonant frequency
(iii) by what percent does the parallel resonant frequency exceed the series resonant frequency?
(iv) Find the Q-factor of the crystal.

Soln:

(i) $$f_s = \frac{1}{2\pi\sqrt{LC}} = \frac{1}{2\pi\sqrt{0.4\times0.085\times10^{-12}}} = 0.856\,MHz.$$

(ii) $$C_{eq} = \frac{C\,C_M}{C+C_M} = \frac{0.085\times10^{-12}\times1\times10^{-12}}{0.085\times10^{-12}+1\times10^{-12}} = 0.078\,PF.$$

$$\therefore f_p = \frac{1}{2\pi\sqrt{L\,C_{eq}}} = \frac{1}{2\pi\times\sqrt{0.4\times0.078\times10^{-12}}} = 0.899\,MHz.$$

(iii) $$\%\ \text{increase} = \frac{0.899-0.856}{0.856}\times100 = 5.023\,\%.$$

(iv) $$Q = \frac{\omega_s L}{R} = \frac{2\pi f_s L}{R} = \frac{2\pi\times0.856\times10^{6}\times0.4}{5\times10^{3}} = 430.272$$