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Subject : **Analog Circuits (EC-405)**

Unit : **I**

Topic : **Oscillator**

UNIT – I

Feedback Amplifier and Oscillators

1.8 Oscillator:

Any circuit that generates an alternating signal is called oscillator. To generate ac signal, the circuit is supplied energy from a dc source. The oscillators have variety of applications. In some application we need signal of low frequencies, in other of very high frequencies. For example, to test the performance of a stereo amplifier, we need an oscillator of variable frequency in audio range (20Hz – 20kHz), which is called audio frequency generator. Generation of high frequency is essential in all communication system. For example in radio and television broadcasting, the transmitter radiates the signal using a carrier of very high frequency. Some applications of communication system with their frequency band is given below.

550 kHz – 22 MHz	Radio broadcasting
88 MHz – 108 MHz	for FM radio
1 GHz – 4 GHz	for DTH, TV and satellite Communication

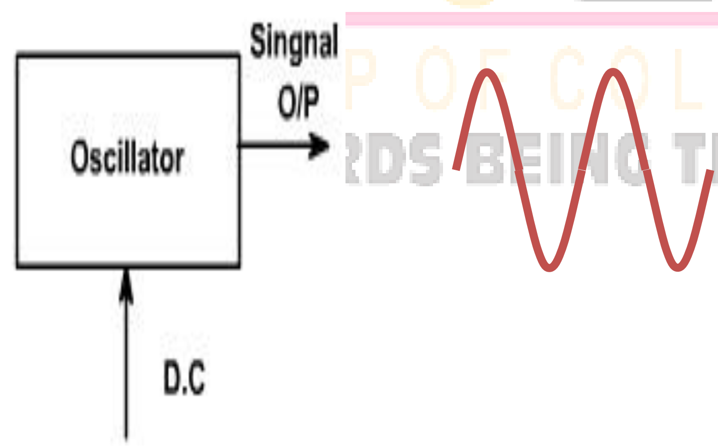

Figure 1.18: Block diagram of Oscillator

Figure 1.18 shows that oscillator is an electronics source of alternating current or voltage having sine, square or saw tooth waves. Oscillator is a circuit which generates an ***ac*** source without requiring any externally applied input signal. It is a circuit which converts ***dc*** energy into ***ac*** energy at very high frequency.

1.9 Comparison between Amplifier and Oscillator:

Comparision between an amplifier and an oscillator is explained in table 2.

Amplifier	Oscillator
1. An amplifier produces an output signal whose waveform is similar to input signal.	1. An oscillator produce an output signal without any input signal
2. Amplifier is an energy convertor; the process of energy conversion is controlled by the input signal.	2. Oscillator does not require an external signal to maintain energy conversion process.
3. If there is no input signal, there is no energy conversion and hence there is no output.	3. It keeps producing an output signal if the source is removed out.
	4. Frequency of the output signal is determined by the passive components used in the oscillator.

1.10 Classification of Oscillator:

Electronic oscillator may be broadly divided into following two group:

(i) **Sinusoidal or harmonic oscillator** which produce an output having sine waveforms as shown in figure 1.19.

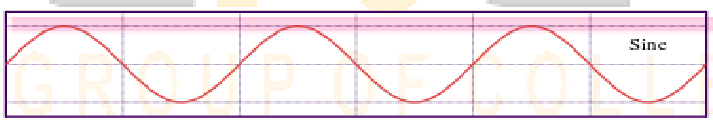

Figure 1.19 Sinusoidal wave

(ii) **Non-Sinusoidal or relaxation oscillator** they produce an output which has square, saw tooth, triangular waveforms etc.

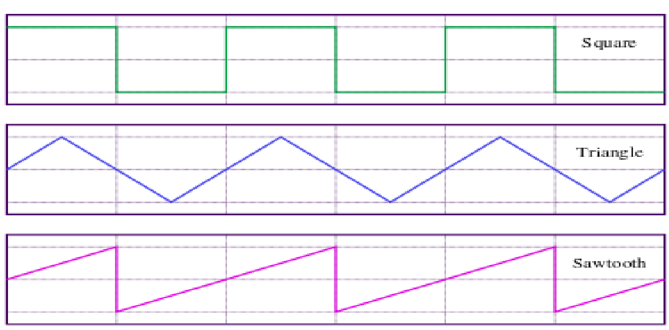

Figure 1.19 Non-Sinusoidal waves

Oscillator may further classified based on their construction into following category:

(i) Tuned circuits or LC oscillators such as Hartley, Colpitts and clapp oscillator.

(ii) R-C oscillators such as R-C phase shift and Wien bridge oscillator.

(iii) Negative resistance oscillators such as tunnel diode oscillator and UJT relaxation oscillator.

(iv) Crystal oscillator.

(v) Multivibrators such as astable, monostable and bistable multivibrator.

Oscillator may also be classified based on frequency of oscillation as:

(i)	Audio frequency oscillator	: up to 20kHz.
(ii)	Radio frequency oscillator	: 20kHz to 30MHz.
(iii)	Very high frequency oscillator	: 30MHz to 300MHz
(iv)	Ultra high frequency oscillator	: 300MHz to 3GHz
(v)	Microwave frequency oscillator	: above 3GHz

1.11 Tank Circuit or Tuned Circuit:

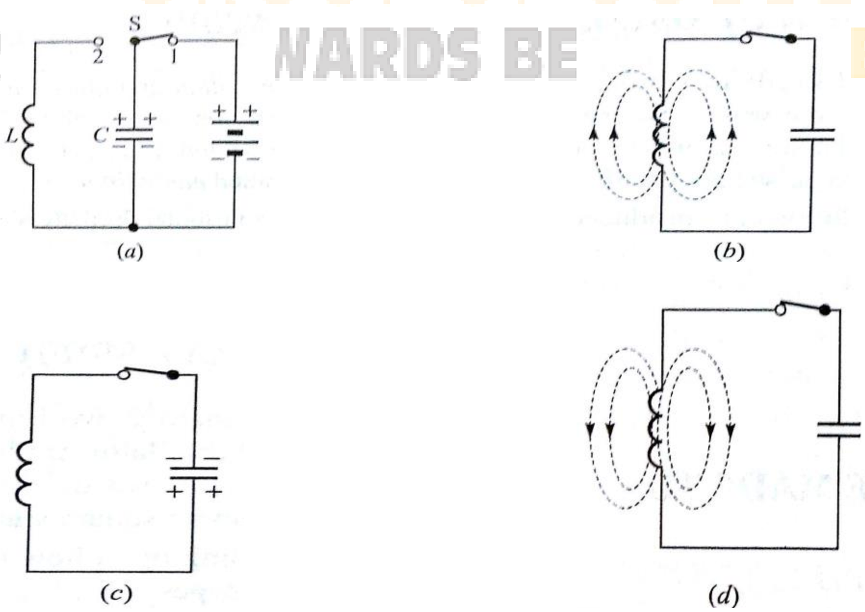

Figure 1.20 Working of Tank Circuit

Tank circuit is also known as frequency determining network, it is design with a capacitor and an inductor connected in parallel. As shown in fig. 1.20(a) energy is introduced into this circuit by connecting the capacitor to a DC voltage source. The capacitor is charged by DC source and there is a voltage across it. We say that energy is stored in the capacitor in the form of *electro-static energy*.

When the switch S is thrown to position 2, current start flowing in the circuit. The capacitor now starts discharging through inductor. Since the inductor has the property of opposing any change in current, the current build up slowly. Maximum current flows in the circuit when the capacitor is fully discharge. At this instant, electro-static energy is converted into *electro-magnetic energy* around the coil as shown in fig. 1.20(b).

Once the capacitor is fully discharged, the magnetic field begins to collapse. The back emf in the inductor keeps the current flowing in the same direction. The capacitor starts charging, but with opposite polarity this time as shown in fig 1.20(c). As the charge builds up across the capacitor, the current decreases and the magnetic field decrease. Once again all the energy in the form of electro-static energy.

The capacitor now begins to discharge again. This time current flows in the opposite direction. Fig. 1.20(d) shows the capacitor fully discharged, and maximum current flowing in the circuit. Again all the energy is in form of electro-magnetic energy. The interchange of *'Oscillation'* of energy between *L* and *C* is repeated again and again. Since some energy is lost during interchange, the amplitude of each half cycle goes on decreasing. Hence we get ***damped oscillation*** as shown in figure 1.21.

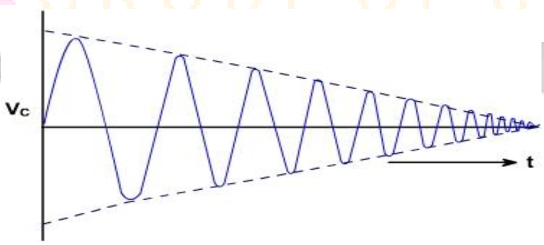

Figure 1.21 Damped Oscillations

The oscillation of LC tank circuit can be maintained at a constant level. For this we have to supply a pulse of energy at the right time in each cycle. The resulting undamped oscillations are called ***sustained oscillation.***

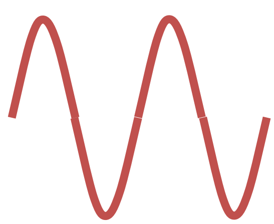

Figure 1.21 Sustained Oscillations

1.11.1 Frequency of Oscillation: Frequency of oscillation is also known as resonant frequency of tank circuit it can be determine as.

At resonance both inductive and capacitive reactance are equal.

$$X_L = X_C \qquad (1)$$

$$2\pi f_o L = \frac{1}{2\pi f_o C} \qquad (2)$$

$$f_o^2 = \frac{1}{4\pi LC}$$

It gives $$\boxed{f_o = \frac{1}{2\pi\sqrt{LC}}} \qquad (3)$$

where L – Inductance of inductor (in Henry)
C – Capacitance of capacitor (in Farad)
f_o – Frequency of oscillation (in Hertz)

1.11.2 Barkhausen Criterion:

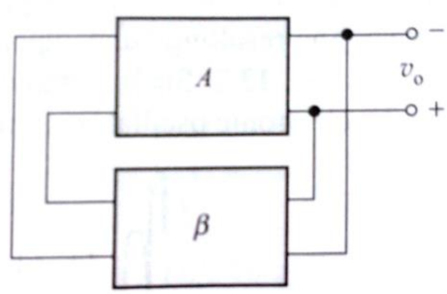

Figure 1.22 Barkhusen Criterion

An oscillator generates AC output signal without any input AC signal. A part of output is feedback to the input positively. This feedback signal is the only input to the internal amplifier. To find necessary condition for the sustained oscillations, positive feedback is required.

The overall gain of positive feedback amplifier is given by

$$A_f = \frac{V_o}{V_{in}} = \frac{A}{1-A\beta}$$

Since $V_{in} = 0$

$$1 - A\beta = 0$$

Or $$\boxed{A\beta = 1} \quad (4)$$

Hence the essential conditions for maintaining oscillation are:

(a) The magnitude of loop gain must be unity $A\beta = 1$.

(b) The total phase shift around the closed loop is 0° or 360°.

1.12 General form of an Oscillator:

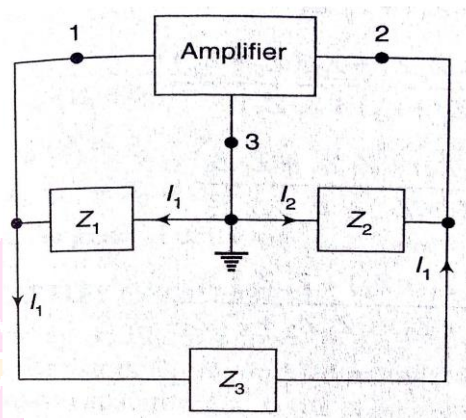

Figure 1.23 General form of oscillator

Figure 1.23 shows the general form of the oscillator. Any of the active devices such as Vacuum tube, Transistor, FET and Op-Amp may be used in the amplifier section. Z_1, Z_2 and Z_3 are reactive elements constituting the feedback tank circuit, which determine the frequency of oscillation.

Frequency of oscillation of the LC oscillator is given by:

$$f_o = \frac{1}{2\pi\sqrt{LC}} \quad (5)$$

Z_1 and Z_2 serves as voltage divider for output voltage and feedback signal. Therefore, the voltage across Z_1 is the feedback signal. The feedback fraction is given by:

$$\beta = \frac{Z_1}{Z_2} \quad (6)$$

1.13 Hartley Oscillator

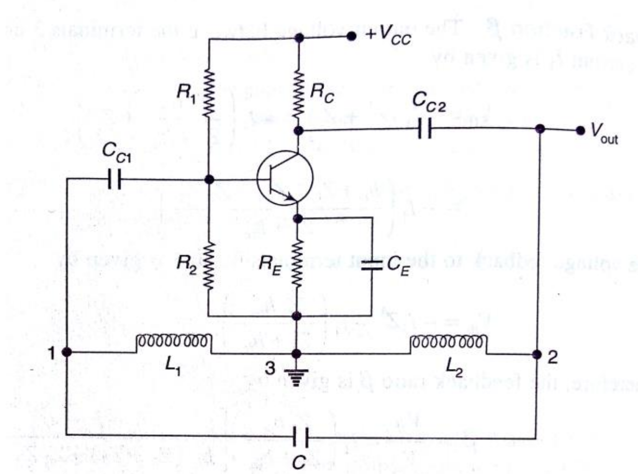

Figure 1.24 Hartley oscillator

Construction

By comparing general form of oscillator with figure1.24 $Z_1$and Z_2 are inductors and Z_3 is a capacitor. Resistor R_1, R_2 and R_E provides necessary dc bias to the transistor. C_E is a bypass capacitor. C_{C1} and C_{C2} are coupling capacitors. The feedback network consisting of inductors L_1, L_2 and a capacitor C determines the frequency of oscillation.

Working

When the supply voltage **+V**$_{CC}$ is switched ON, a transient current is produced in tank circuit and consequently, damped oscillation are set up in the circuit. The oscillatory current in the tank circuit produces ac voltages across L_1 and L_2. As terminal 3 is at ground potential, voltage developed at terminal 1is positive and it is at terminal 2 is negative with respect to ground. Thus the phase difference between the terminal 1 and 2 is 180̊. In the CE mode the transistor provides a phase difference of 180̊. Therefore the total phase shift is 360̊. Thus the necessary condition for sustained oscillation is satisfied. If the feedback is adjusted so that the loop gain Aβ = 1, the circuit acts as an oscillator.

The frequency of oscillation is given by:

$$\boldsymbol{f_o = \frac{1}{2\pi\sqrt{L_{eq}C}}} \qquad (7)$$

where $L_{eq} = L_1 + L_2$

Since the output voltage appears across L_2 and the feedback voltage across L_1, the feedback fraction is given by:

$$\beta = \frac{Z_1}{Z_2} = \frac{X_{L1}}{X_{L2}} = \frac{L_1}{L_2} \quad (8)$$

1.14 Colpitts Oscillator

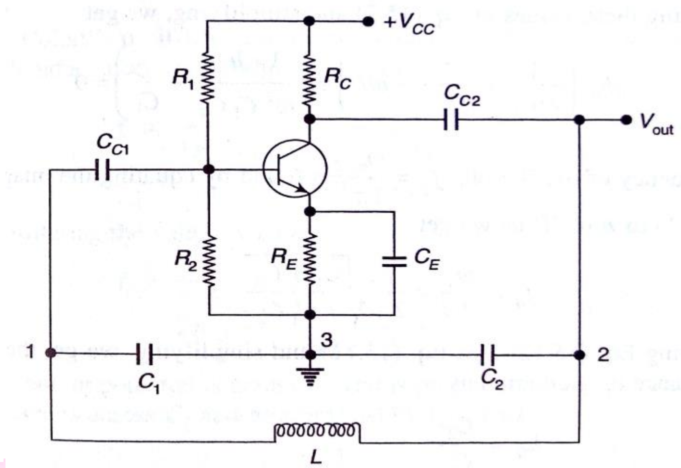

Figure 1.25 Colpitts oscillator

Construction

By comparing general form of oscillator with figure1.25 $Z_1$and Z_2 are capacitors and Z_3 is an inductor. Resistor R_1, R_2 and R_E provides necessary dc bias to the transistor. C_E is a bypass capacitor. C_{C1} and C_{C2} are coupling capacitors. The feedback network consisting of capacitors C_1, C_2 and an inductor L determines the frequency of oscillation.

Working

When the supply voltage +V_{CC} is switched ON, a transient current is produced in tank circuit and consequently, damped oscillation are set up in the circuit. The oscillatory current in the tank circuit produces ac voltages across C_1 and C_2. As terminal 3 is at ground potential, voltage developed at terminal 1is positive and it is at terminal 2 is negative with respect to ground. Thus the phase difference between the terminal 1 and 2 is 180̊. In the CE mode the transistor provides a phase difference of 180̊. Therefore the total phase shift is 360̊. Thus the necessary condition for sustained oscillation is satisfied. If the feedback is adjusted so that the loop gain Aβ = 1, the circuit acts as an oscillator. Since the output voltage appears across C_2 and the feedback voltage across C_1, the feedback fraction is given by

$$\beta = \frac{Z_1}{Z_2} = \frac{X_{C1}}{X_{C2}} = \frac{C_2}{C_1} \quad (9)$$

The frequency of oscillation is given by:

$$f_o = \frac{1}{2\pi\sqrt{LC_{eq}}} \tag{10}$$

Where $$C_{eq} = \frac{C_1 C_2}{C_1 + C_2}$$

1.15 RC Oscillators

All the oscillators using tuned LC circuit operates on high frequencies. At low frequency, inductors and capacitors required for the time circuit would be very bulky. RC oscillators found to be more suitable. Two important RC oscillators are:-

(i) RC Phase shift oscillator and

(ii) Wien bridge oscillator

1.15.1 RC Phase Shift Oscillator

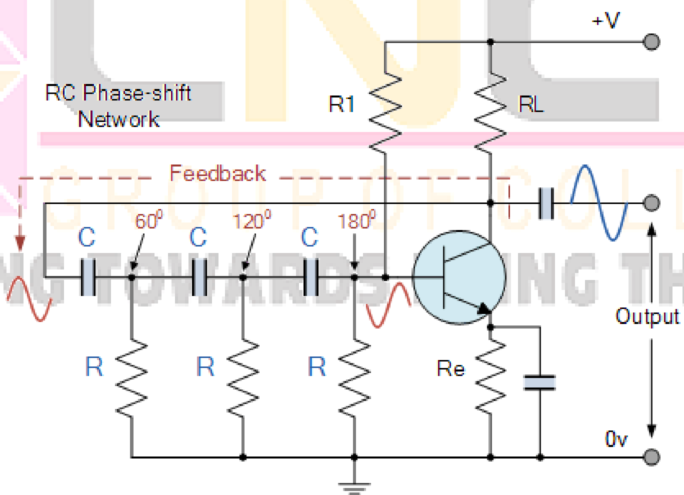

Figure 1.26 RC Phase Shift Oscillator

In RC phase shift oscillator as shown in figure 1.26 the required phase shift of 180° in the feedback loop from output to input is obtained by using R and C components instead of tank circuit. As shown in figure RC phase shift oscillator uses cascade connection of high pass filter. This oscillator is designed by three RC section followed by a common emitter amplifier. The phase difference Φ for each section is given by:

$$\emptyset = \tan^{-1}\left(\frac{1}{\omega CR}\right) \tag{11}$$

Each RC network provides a phase difference of Φ which is between 0 – 90̊. If R is adjusted such that Φ becomes 60̊. If the value of R and C are so chosen that, for the given frequency f_o, the phase shift of each RC section is 60̊. Thus such a RC ladder network produces a total phase shift of 180̊ between the input and output voltage for given frequency. The other 180̊ phase shift is provided by transistor in common emitter mode. In this way the total phase shift in loop is 360̊ or 0̊. Thereby satisfying the Barkhausen criterion for oscillation.

The frequency of oscillation is given by:

$$\boldsymbol{f_o = \frac{1}{2\pi RC\sqrt{6}}} \quad \textbf{(12)}$$

At this frequency it is found that feedback factor of network is

$$\boldsymbol{|\beta| = \frac{1}{29}} \quad \textbf{(13)}$$

In order that |Aβ| shall not be less than unity, it is require that the amplifier gain |A| must be more than 29 for sustained oscillation.

Frequency of RC Phase Shift Oscillator

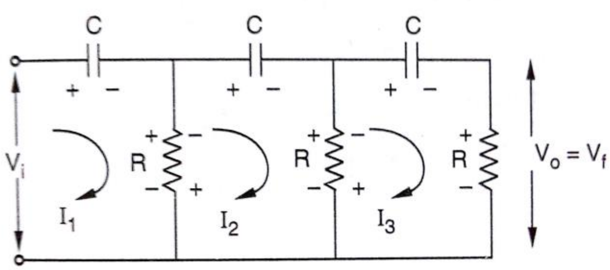

Figure 1.26 RC Cascaded Network

Applying KVL to various loops we get,

$$I_1\left(R + \frac{1}{j\omega C}\right) - I_2R = V_1$$

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

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

Replacing *jω* by s and writing the equations in matrix form,

$$\begin{bmatrix} R+\frac{1}{sC} & -R & 0 \\ -R & 2R+\frac{1}{sC} & -R \\ 0 & -R & 2R+\frac{1}{sC} \end{bmatrix} \begin{bmatrix} I_1 \\ I_2 \\ I_3 \end{bmatrix} = \begin{bmatrix} V_i \\ 0 \\ 0 \end{bmatrix}$$

by applying Cramer's rule, I_3 is given as

$$I_3 = \frac{V_i s^3 R^2 C^3}{1+5sRC+6s^2C^2R^2+s^3C^3R^3}$$

now

$$V_o = V_f = I_3 R = \frac{V_i s^3 R^3 C^3}{1+5sRC+6s^2C^2R^2+s^3C^3R^3}$$

Feedback factor is
$$\beta = \frac{V_f}{V_i} = \frac{s^3R^3C^3}{1+5sRC+6s^2C^2R^2+s^3C^3R^3}$$

Replacing ***s*** by ***jω***
$$\beta = \frac{-j\omega^3R^3C^3}{1+5j\omega RC-6\omega^2C^2R^2-j\omega^3C^3R^3}$$

Dividing numerator and denominator by $-j\omega^3R^3C^3$ and replacing $1/\omega RC$ by α we get

$$\beta = \frac{1}{1+6j\alpha-5\alpha^2-j\alpha^3}$$

$$\beta = \frac{1}{(1-5\alpha^2)+j\alpha(6-\alpha^2)}$$

To have phase shift of 180̊, the imaginary part in the denominator must be zero.

hence $\alpha(6-\alpha^2) = 0$

Which gives $\alpha^2 = 6$

Or $\alpha = \sqrt{6}$

$$\frac{1}{\omega RC} = \sqrt{6}$$

$$\omega = \frac{1}{RC\sqrt{6}}$$

Thus the frequency of oscillation is

$$\boxed{\boldsymbol{f_o = \frac{1}{2\pi RC\sqrt{6}}}}$$

At this frequency $\beta = \frac{1}{1-5\times\left(\sqrt{6}\right)^2} = -\frac{1}{29}$

Or $\boxed{\boldsymbol{|\beta| = \frac{1}{29}}}$

Now to have oscillation $|A\beta| \geq 1$

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

$$|A| \geq \frac{1}{|\beta|} \geq \frac{1}{\frac{1}{29}}$$

Thus $\boxed{\boldsymbol{|A| \geq 29}}$

1.15.2 Wien Bridge Oscillator

Construction

It is one of the most popular type of oscillator used in audio frequency range. This type of oscillator is simple in design, compact in size, and remarkable stable in its frequency output. Furthermore, its output is relatively free from distortion and its frequency can be varied easily. Frequency output of typical Wien bridge oscillator is only about 1MHz. Lead Lag network produce signal of 0° phase shift, which satisfy the Barkhausen criterion.

Wien Bridge Oscillator Circuit

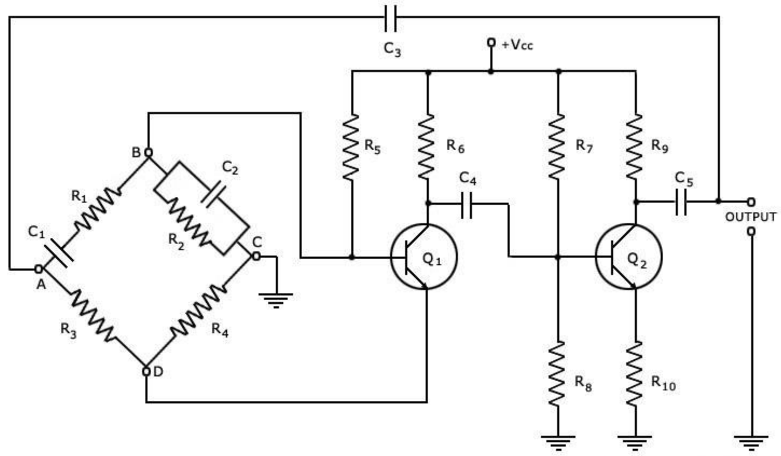

Figure 1.27 Wien Bridge Oscillator

Feedback ratio of lead lag network is 1/3. Hence to satisfy the condition of unity loop gain, gain of amplifier must be at least 3. To achieve the required gain we can use two common emitter transistor amplifier or an operational amplifier in non-inverting mode.

Working

As shown in the figure 1.27, it is a two stage amplifier with an RC bridge circuit. By adding Wien bridge feedback network, the oscillator becomes sensitive to a signal of only one particular frequency. This particular frequency is that at which Wien bridge is balanced and for which the phase shift is 0°. The feedback network is employed in the circuit to increase frequency stability. When we switch on the **+Vcc** supply, a resonating current of frequency $\frac{1}{2\pi RC}$ flows in the bridge circuit. The current is amplified to achieve the Barkhausen criterion. Since transistor amplifier in CE mode gives 180° phase shift, and the phase shift of bridge circuit is 0°, hence to feedback positive signal to bridge circuit 180° phase shift is required which is provided by another transistor in CE mode. And finally we get sinusoidal signal of stable frequency.

Frequency of oscillation can also be determined by the bridge circuit of oscillator. Bridge is balanced only when

$$R_3\left[\frac{R_2}{1+j\omega C_2R_2}\right] = R_4\left[R_1 - \frac{j}{\omega C_1}\right]$$

$$R_2R_3 = R_4(1+j\omega C_2R_2)(R_1 - \frac{j}{\omega C_1})$$

$$R_2R_3 = R_4R_1 - \frac{jR_4}{\omega C_1} + j\omega C_2R_2R_1R_4 + \frac{C_2}{C_1}R_2R_4$$

$$R_2R_3 - R_4R_1 - \frac{C_2}{C_1}R_2R_4 + \frac{jR_4}{\omega C_1} - j\omega C_2R_2R_1R_4 = 0$$

Separating real and imaginary parts

$$R_2R_3 - R_4R_1 - \frac{C_2}{C_1}R_2R_4 = 0$$

Which gives $\frac{R_3}{R_4} = \frac{C_2}{C_1} + \frac{R_1}{R_2}$

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

$$\boxed{R_3 = 2R_4} \qquad (14)$$

And $\frac{R_4}{\omega C_1} - \omega C_2R_2R_1R_4 = 0$

$$\omega^2 = \frac{1}{C_1C_2R_1R_2}$$

$$\omega = \frac{1}{\sqrt{C_1C_2R_1R_2}}$$

$$f = \frac{1}{2\pi\sqrt{C_1C_2R_1R_2}}$$

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

$$\boxed{f = \frac{1}{2\pi RC}} \qquad (15)$$

1.16 Crystal Oscillator

Most communications and digital applications require the use of oscillators with extremely stable output. Crystal oscillators are invented to overcome the output fluctuation experienced by conventional oscillators. Some crystals found in nature exhibit the piezoelectric effect. When an ac voltage is applied across them, they vibrate at the frequency of the applied voltage. Conversely, if they are mechanically pressed, they generate an ac voltage. The main substances that produce this piezoelectric effect are Quartz, Rochelle salts, and Tourmaline.

Rochelle salts have greatest piezoelectric activity, for a given ac voltage, they vibrate more than quartz or tourmaline. They are used in microphones, headsets and loudspeakers.

Tourmaline shows the least piezoelectric activity but is a strongest of the three. It is most expensive and used at very high frequencies.

Quartz is a compromise between the piezoelectric activity of Rochelle salts and the strength of tourmaline. It is inexpensive and easily available in nature. It is most widely used for RF oscillators and filters.

The natural shape of a quartz crystal is a hexagonal prism with pyramids at the ends. To get a useable crystal out of this it is sliced in a rectangular slab form of thickness t. For use in electronic circuits, the slab is mounted between two metal plates. The fundamental frequency of a crystal is given by

$$\boldsymbol{f} = \frac{\mathbf{1}}{\boldsymbol{t}} \qquad (16)$$

where $\boldsymbol{t}$ is thickness of crystal.

1.16.1 AC Equivalent Circuit of Crystal

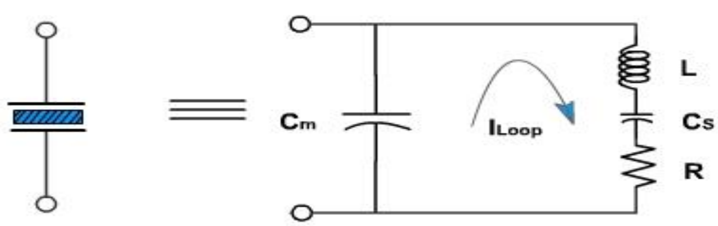

Figure 1.28 AC Equivalent Circuit of Crystal

When the mounted crystal is not vibrating, it is equivalent to a capacitance C_m, because it has two metal plates separated by dielectric, C_m is known as mounting capacitance. When the crystal is vibrating, it acts like a tuned circuit. Figure shows the ac equivalent circuit of a crystal vibrating at or near its fundamental frequency. Typical values are L is henrys, C_s in fractions of a Pico farad, R in hundreds of ohms and C_m in Pico farads. The Q of the circuit is very high, compared with L-C tank circuit. Because of very high Q, a crystal leads to oscillators with very stable frequency values.

The crystal can have two resonant frequencies as shown in figure 1.29.

(i) series resonance frequency
(ii) parallel resonance (or anti-resonance) frequency

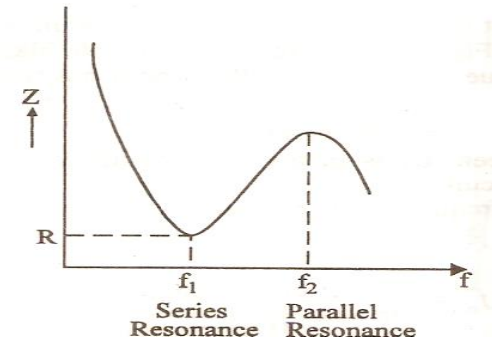

Figure 1.29 Resonant frequency

Series resonance frequency f_1 occurs when $X_L = X_C$. At this frequency, crystal offers very low impedance to the external circuit where Z = R. it is given by:

$$f_1 = \frac{1}{2\pi\sqrt{LC_s}} \qquad (17)$$

Parallel resonance (or anti-resonance) frequency f_2 occurs when reactance of the series leg equals the reactance of C_m. At this frequency, crystal offers very high impedance to the external circuit. It is given by

$$f_2 = \frac{1}{2\pi\sqrt{LC_p}} \qquad (18)$$

Where $C_p = \frac{C_m C_s}{C_m + C_s}$

1.16.2 Pierce Crystal Oscillator

The Colpitts oscillator can be modified by using the crystal to behave as an inductor. The circuit is called Pierce crystal oscillator. The crystal behaves as an inductor for a frequency slightly higher than the series resonance frequency. 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.

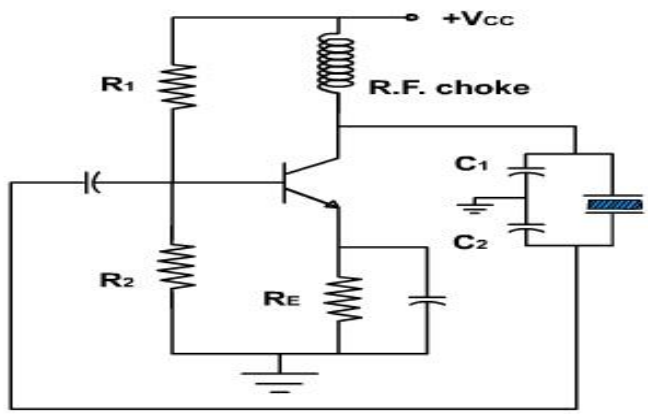

Figure 1.30 Pierce Crystal Oscillator

As shown in figure 1.30, Resistors R_1, R_2, and R_E provide a voltage-divider stabilized dc bias circuit. Capacitor C_E provides ac bypass of the emitter resistor to avoid degeneration. The RFC coil provides dc collector load and also prevents any ac signal entering from the dc supply. The coupling capacitor C_C has negligible reactance at circuit operating frequency but blocks any dc flow between collector and base. The resulting frequency is set by the series resonant frequency of the crystal. Crystal oscillator provides good frequency stability, and there no effect of change in supply voltage, temperature transistor parameters etc.

Tutorials

1. In the Hartley oscillator L_2 = 0.4mH and C = .004μF. If the frequency of oscillation is 120kHz, find the value of L_1. Neglect the value of mutual inductance. ***(.04mH)***
2. In a transistorized Hartley oscillator, the two inductors are 2mH and 20μH, while frequency is to be changed from 950kHz to 2050kHz. Calculate the range over which capacitor is to be varied. ***(2.98pF – 13.89pF)***
3. In a Hartley oscillator, the value of capacitor in the tuned circuit is 500pF and the two section of coil have inductances 12μH and 38μH. Find the frequency of oscillation and the feedback factor β. ***(1MHz, .316)***
4. In a Hartley oscillator, L_2 =15mH and C = 50pF. Calculate L_1 for a frequency of 168kHz. The mutual inductance between L_1 and L_2 is 5μH. Also find the required feedback factor for the oscillation. ***(2.945mH, 0.196)***

5. In the Colpitts oscillator, $C_1 = 0.2\mu F$ and $C_2 = 0.02\mu F$. If the frequency of oscillation is10kHz, find the value of the inductor. Also find the required feedback for oscillation. ***(13.932mH, 0.1)***
6. A Colpitts oscillator is designed with $C_2 = 100pF$ and $C_1 = 7500pF$. The inductance is variable. Determine the range of inductor the frequency of oscillation is to vary between 950kHz to 2050kHz. ***(61µH-284µH)***
7. In an RC phase shift oscillator, if $R_1 = R_2 = R_3 = 200k\Omega$ and $C_1 = C_2 = C_3 = 100pF$. Find the frequency of oscillation ***(3.248kHz)***
8. In an RC phase shift oscillator, if its frequency of oscillation is 955Hz and $R_1 = R_2 = R_3 = 680k\Omega$, find the value of capacitor used. ***(100pF)***
9. In a Wien bridge oscillator, if the value of R is $100k\Omega$, and frequency of oscillation is 10kHz. Find the value of capacitor. ***(159pF)***
10. The frequency sensitive arm of the Wien 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 value of R_2.
(1.013kΩ, 25.33kΩ)
11. A crystal has following parameters:- L = 0.4H, C = 0.085pF and C_m = 1pF with R = 5kΩ. find
(i) Series resonant frequency
(ii) Parallel resonant frequency
(iii) Q factor of coil. ***(856kHz, 899kHz, 430.27)***
12. A crystal has L = 2H, C = 0.01pF, and R = 2kΩ. Its mounting capacitance is 2pF. calculate its series and parallel resonating frequency. ***(1.125MHz, 1.128MHz)***