13 Signal Generators and Analysers

13.1 INTRODUCTION

Signal generators provide a variety of waveforms for testing of electronic circuits at low power levels. There are various types of signal generators, but the following characteristics are common to all types:

1. Always a stable generator with desired frequency signals should be generated.
2. Generated signal amplitude should be regulated over a wide range from very small to relatively large level.
3. Generated signal should be free from any distortions.

There are many variations of the above requirements, especially for specialised signal generators such as function generators, pulse generators and pulse frequency generators. Sine wave generators, both in audio and radio frequency ranges are called oscillators. Although, the terminology is not universal, the term *oscillator* is generally used for an instrument that provides only a sinusoidal output signal. The term *function generator* is applied to an instrument that provides several output waveforms, including sine wave, square wave, triangular wave and pulse trains as well as amplitude modulation of the output signal.

13.2 OSCILLATORS

Oscillator is the basic element of ac signal sources and generates sinusoidal signals of known frequency and amplitude. The main applications of oscillators are as sinusoidal waveform sources in electronic measurement work. Oscillators can generate a wide range of frequencies (few Hz to many GHz) as per the requirement of the application. Although an oscillator can be considered as generating sinusoidal signal, it is to be noted that it merely acts as an energy converter. It converts a dc source of supply to alternating current of desired frequency.

Oscillators are generally an amplifier with positive feedback. An oscillator has a gain equal to or slightly greater than unity. In the feedback path of the oscillator, capacitor, inductor or both are used as reactive components. In addition to these reactive components, an operational amplifier or bipolar transistor is used as amplifying device. No external ac input is required to cause the oscillator to work as the dc supply energy is converted by the oscillator into ac energy.

Oscillators may be classified in a number of ways. Here they are classified on three bases: (a) the design principle used, (b) the frequency range over which they are used, and (c) the nature of generated signals.

1. Classification According to Design Principle

(a) Positive feedback oscillators (b) Negative feedback oscillators

2. Classification According to Frequency Band of the Signals

(a) Audio Frequency (AF) oscillators—frequency rage is 20 Hz to 20 kHz

(b) Radio Frequency (RF) oscillators—frequency range is 20 kHz to 30 MHz

(c) Video Frequency oscillators—frequency range is dc to 5 MHz

(d) High Frequency (HF) oscillators—frequency range is 1.5 MHz to 30 MHz

(e) Very High Frequency (VHF) oscillators—frequency range is 30 MHz to 300 MHz

3. Classification According to Types of Generated Signals

(a) Sinusoidal Oscillators These are known as harmonic oscillators and are generally *LC* tuned-feedback or *RC* tuned-feedback type oscillator that generates a sinusoidal waveform which is of constant amplitude and frequency.

(b) Non-sinusoidal Oscillators These are known as relaxation oscillators and generate complex non-sinusoidal waveforms that changes very quickly from one condition of stability to another such as square-wave, triangular-wave or sawtooth-wave-type waveforms.

13.2.1 Feedback Circuit Employed in Oscillators

It is the use of positive feedback that results in a feedback amplifier having closed-loop gain A_f greater than unity and satisfies the phase condition.

In a system assuming, V_{in} and V_{out} as the input and output voltages respectively. Without feedback or open-loop gain,

$$A_v = \frac{V_{out}}{V_{in}}$$

$$\therefore \quad V_{out} = A_v V_{in}$$

Taking the forward path gain of the system as A and β as feedback factor

With feedback, the output voltage of the system,

$$V_{out} = A_v(V_{in} + \beta V_{out})$$

$$\therefore \quad V_{out} = A_v V_{in} + A_v \beta V_{out}$$

$$\therefore \quad V_{out}(1 - A_v \beta) = A_v V_{in}$$

$$A_f = \frac{V_{out}}{V_{in}} = \frac{A_v}{1 - A_v \beta}$$

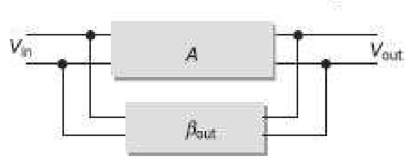

Figure 13.1 *Basic feedback circuit employed in oscillators*

Oscillators generate a continuous voltage output waveform at a required frequency with the values of the inductors, capacitors or resistors forming a frequency selective *LC* resonant (or tank) feedback network. The oscillator frequency is regulated using a tuned or resonant inductive/capacitive circuit with the resulting output frequency being known as the oscillation frequency. So, the feedback path of the oscillator is made reactive. The phase angle of the feedback will vary as a function of frequency and this is called *phase shift.* Certain conditions are required to fulfill for sustained oscillations and these conditions are that (a) the loop gain of the circuit must be equal to or greater than unity, and (b) the phase shift around the circuit must be zero. These two conditions for sustained oscillations are called *Barkhausen criteria.*

13.2.2 Resonance

If a constant voltage with varying frequency is impressed to a circuit consisting of an inductor, capacitor and resistor, then the reactance of both the capacitor-resistor *(RC)* and inductor-resistor (*RL*) paths are to change both in amplitude and in phase of the output signal as compared to the input signal. At high frequencies the reactance of a capacitor is very low and it acts as a short circuit while the reactance of the inductor is high and it acts as an open circuit. At low frequencies, the reverse is true, meaning the reactance of the capacitor acts as an open circuit and the reactance of the inductor acts as a short circuit. Between these two boundaries, the combination of the inductor and capacitor produces a tuned or resonant circuit that has a resonant frequency (f_r) in which the capacitive and inductive reactances are equal and cancel out each other, leaving only the resistance of the circuit to oppose the flow of current and as a result of that, there is no phase shift as the current is in phase with the voltage. Based on this concept subsequent sections of the chapter are explained.

13.2.3 Basic *LC* Oscillatory Circuit

As shown in Figure 13.2, the circuit consists of an inductive coil *L* and a capacitor *C*. The capacitor stores energy in the form of an electrostatic field and which produces a potential or *static voltage* across it, while the inductive coil stores its energy in the form of a magnetic field. The capacitor is charged up to the dc supply voltage *V* by putting the switch in the position *A.* When the capacitor is fully charged, the switch is thrown to the position *B* and the charged capacitor is now connected in parallel across the inductive coil so the capacitor begins to discharge itself through the coil. The voltage across *C* starts falling as the coil. The voltage across *C* starts falling as the current through the coil begins to rise. This rising current sets up an electromagnetic field around the coil and when *C* is completely discharged, the energy that was originally stored in the capacitor *C* as an electrostatic field is now stored in the inductive coil *L* as an electromagnetic field around the coil windings. As there is now no external voltage in the circuit to maintain the current within the coil, it starts to fall as the electromagnetic field begins to collapse. A back emf is induced in the coil ($e = -L di/dt$) keeping the current flowing in the original direction. This current now charges the capacitor *C* with the opposite polarity to its original charge. *C* continues to charge until the current has fallen to zero and the electromagnetic field of the coil has collapsed completely. The energy originally introduced into the circuit through the switch has been returned to the capacitor which again has an electrostatic potential across it, although it is now of the opposite polarity. The capacitor now starts to discharge again back through the coil and the whole process is repeated, with the polarities changed and continues as the energy is passed back and forth producing an ac type sinusoidal voltage and current waveform.

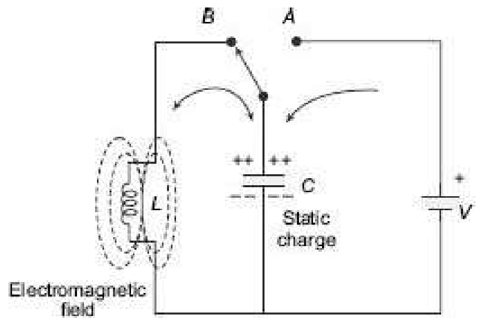

Figure 13.2 *Basic LC oscillator circuit*

This oscillatory action of transferring energy from the capacitor *C* to the inductor, *L* and vice versa, would continue indefinitely if there is no loss of energy in the circuit. But, energy is lost in the resistance of the inductor coil, in the dielectric of the capacitor, and in radiation from the circuit; so the oscillation steadily decreases until it dies away completely. Then in a practical *LC* circuit, the amplitude of the oscillatory voltage decreases at each half cycle of oscillation and will eventually die away to zero. The oscillations are then said to be damped. The quality factor of the circuit sets the amount of damping. In Figure 13.3, damped oscillations are shown in both the cases, with small *R* and with large *R*.

The frequency of the oscillatory voltage depends upon the value of the inductance and capacitance in the *LC* circuit. We know when *resonance* has to occur, both the capacitive X_C and inductive X_L reactances must be equal and opposite to cancel out each other. As a result, the resistance in the circuit remains to oppose the flow of current. Then the frequency at which this will happen is given as

$$X_L = 2\pi f L$$

and $$X_C = \frac{1}{2\pi f C}$$

At resonance, $X_L = X_C$

$$\therefore \quad 2\pi f L = \frac{1}{2\pi f C}$$

$$f^2 = \frac{1}{(2\pi)^2 LC}$$

Resonant frequency in a tuned *LC* circuit, the output frequency, $f_r = \frac{1}{2\pi\sqrt{LC}}$

To maintain the oscillations keeping the amplitude at a constant level, in an *LC* circuit, it is required to replace the energy lost in each oscillation. The amount of energy replaced must be equal to that lost during each cycle. Alternatively, if the amount of energy replaced is too small, the amplitude would decrease to zero over time. The simplest way of replacing this energy is to take part of the output from the *LC* circuit, amplify it and then feed it back into the *LC* circuit again and this can be achieved using a voltage amplifier. To produce a constant oscillation, the level of the energy fed back to the *LC* network must be accurately controlled. Then there must be some form of automatic amplitude or gain control when the amplitude tries to vary from a reference voltage either up or down. To maintain a stable oscillation the overall gain of the circuit must be equal to 1 or unity. Any less and the oscillations will not start or die away to zero, any more the oscillations will occur but the amplitude will become clipped by the supply rails causing distortion. A circuit containing this feature is considered in the next section.

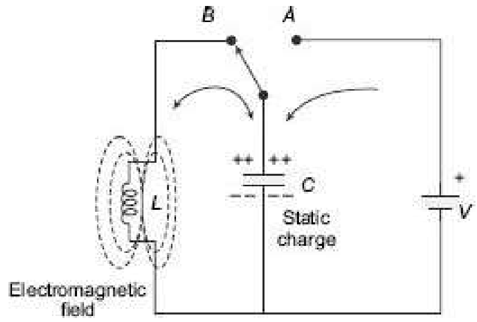

Figure 13.3 *Damped oscillations*

13.2.4 Basic Transistor *LC* Oscillator Circuit

A BJT is used as the oscillator amplifier and the tuned *LC* circuit acts as the collector load as shown in Figure 13.4. A second coil L_2 is connected between the base and emitter. Electromagnetic field of L_2 is mutually coupled with that of the coil L. Mutual inductance exists between two circuits. The changing current in one circuit induces by electromagnetic induction a potential in the other due to transformer action. So as the oscillations take place in the tuned circuit, electromagnetic energy is transferred from the coil L to the coil L_2 and a voltage of the same frequency as that in the tuned circuit is applied between the base and emitter of the transistor. In this way, the necessary automatic feedback voltage is obtained. The amount of feedback can be varied by changing the coupling between coils L and L_2. When the circuit is oscillating, its impedance is resistive and the collector and base voltages are 180° out of phase. In order to maintain oscillations, the voltage applied to the tuned circuit must be in-phase with the oscillations occurring in the tuned circuit. So, it is necessary to introduce an additional 180° phase shift into the feedback path between the collector and base. This is done by winding the coil of L_2 in the correct direction relative to the coil L giving us the correct amplitude and phase relationships for the oscillator circuit or by introducing a phase shift network between the output and input of the amplifier.

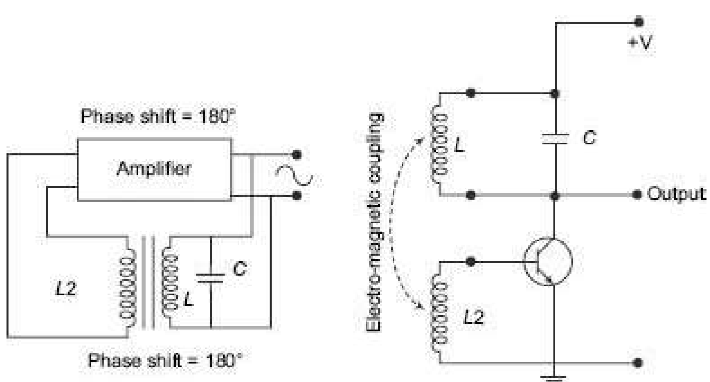

Figure 13.4 *Basic transistor LC oscillator*

LC oscillators are actually sinusoidal oscillators or harmonic oscillators that can generate high-frequency sine waves for use in Radio Frequency *(RF)* Type applications with the transistor amplifier being a BJT or FET. There are different ways to construct *LC* filter networks and amplifiers. As a result, harmonic oscillators come in different forms and the most common forms are Hartley *LC* oscillator, Colpitts *LC* oscillator, Armstrong oscillator, Clapp oscillator, etc.

13.2.5 Oscillator Summary

A few basic requirements for an oscillatory circuit are given as follows:

1. The circuit should contain a reactive or frequency dependent component—either an Inductor (L) or a Capacitor (C) and a dc supply voltage.
2. Overall gain of the amplifier circuit must be at least unity.
3. Self-regenerative or positive feedback results oscillations.
4. Oscillations of the circuit become damped due to circuit losses.
5. To overcome these circuit losses, voltage amplification is necessary.
6. Desired oscillations can be maintained by using some part of the output voltage as feedback to the tuned circuit that is of the correct amplitude and in-phase (0°).
7. To keep the output signal in phase with the input, the overall phase shift of the circuit must be zero.

13.3 HARTLEY OSCILLATOR

The basic *LC* oscillator circuit does not have the option of controlling the amplitude of the oscillations. A weak electromagnetic coupling between L and L_2 results in insufficient feedback and the oscillations would eventually die away to zero. Similarly, a strong feedback causes the oscillations to increase in amplitude until they are limited by the circuit conditions producing distortion. It is possible to feed back exactly the right amount of voltage for constant amplitude oscillations. If the feedback is more than what is necessary, the amplitude of the oscillations can be controlled by biasing the amplifier in such a way that if the oscillations increase in amplitude, the bias is increased and the gain of the amplifier is reduced. If the amplitude of the oscillations decreases, the bias decreases and the gain of the amplifier increases, thus, increasing the feedback. This is the method to keep oscillations constant and it is known as *automatic base bias.* Efficient oscillator can be implemented by employing a class-B or even class-C bias as the collector current flows during only part of the cycle and the quiescent collector current is very small. Then this self-tuning base oscillator circuit forms the basic configuration for the Hartley oscillator circuit.

In the Hartley oscillator, the tuned *LC* circuit is connected between the collector and the base of the transistor amplifier and as far as the oscillatory voltage is concerned, the emitter is connected to a tapping point on the tuned circuit coil. A Hartley oscillator can be implemented from any configuration that uses either a single-tapped coil or a pair of series-connected coils in parallel with a single capacitor.

13.3.1 Basic Hartley Oscillator Circuit

Figure 13.5 shows the basic Hartley oscillator circuit. During oscillation, the voltage at the point X (collector), relative to the point Y (emitter), is 180° out-of-phase with the voltage at the point Z (base) relative to the point Y. At the frequency of oscillation, the impedance of the collector load is resistive and an increase in base voltage causes a decrease in the collector voltage. Then there is a 180° phase change in the voltage between the base and collector and this along with the original 180° phase shift in the feedback loop provides the correct phase relationship of positive feedback for oscillations to be maintained. The position of tapping point of the inductor sets the amount of feedback. If it is moved nearer to the collector, the amount of feedback is increased, but the output taken between the collector and ground is reduced and vice versa. Resistors R_1 and R_2 are there for the usual stabilising dc bias for the transistor in the normal manner while the capacitors act as dc-blocking capacitors. In this circuit, the dc collector current flows through a part of the coil and for this reason, the circuit is said to be series-fed with the frequency of oscillation of the Hartley oscillator being given as

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

where, $L = L_1 + L_2$.

Note: L is the total inductance if two separate coils are used.

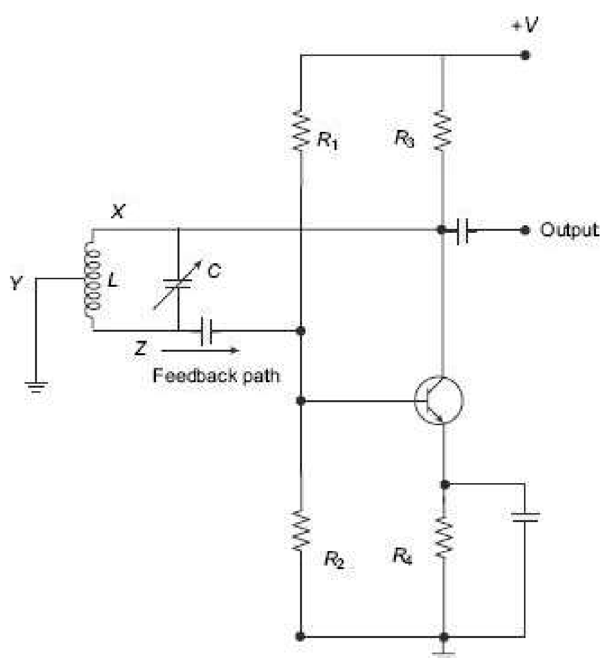

Figure 13.5 *Basic Hartley oscillator*

The frequency of oscillations can be adjusted by varying the tuning capacitor C or by varying the tap position of the inductive coil, giving an output over a wide range of frequencies making it very easy to tune. In the series-fed Hartley oscillator, it is also possible to connect the tuned tank circuit across the amplifier as a shunt-fed oscillator discussed as follows.

13.3.2 Shunt-fed Hartley Oscillator Circuit

As shown in Figure 13.6, in the shunt-fed Hartley oscillator, both the ac and dc components of the collector current have separate paths around the circuit. Here, a very small amount of power is wasted in the tuned circuit. Since the dc component is blocked by the capacitor C_2, no dc component flows through the inductive coil, L. The Radio Frequency Coil (RFC) L_2 is an RF choke which offers a high reactance at the frequency of oscillations so that most of the RF current is applied to the LC tuning tank circuit via the capacitor, C_2 as the dc component passes through L_2 to the power supply. A resistor could be used in place of the RFC coil but the efficiency would be less.

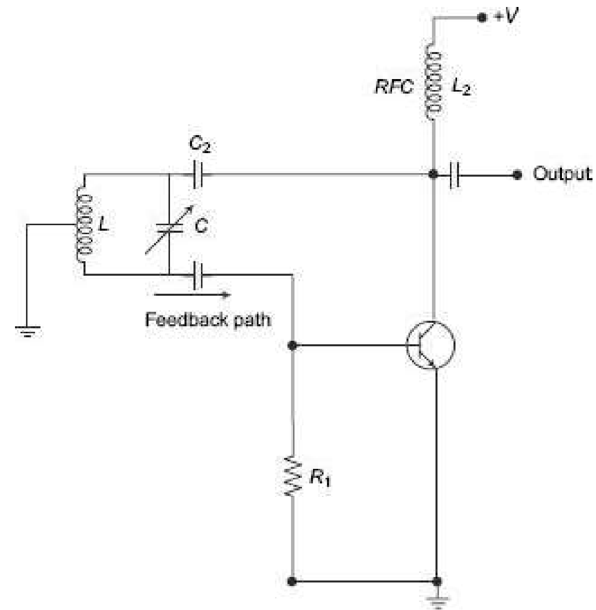

Figure 13.6 *Shunt-fed Hartley oscillator*

Example 13.1

One Hartley oscillator circuit has two inductors of 0.5 mH and each is tuned to resonate with a capacitor which can be varied from 100 pF to 500 pF. Determine the upper and lower frequencies of oscillation and the oscillator bandwidth.

Solution The circuit consists of two inductive coils in series.

The total inductance is given as:

$$L_T = L_1 + L_2 = 0.5 + 0.5 = 1 \text{ mH}$$

Upper frequency, $f_H = \dfrac{1}{2\pi\sqrt{1 \text{ mH} \times 100 \text{ pF}}} = 503 \text{ kHz}$

Lower frequency, $f_L = \dfrac{1}{2\pi\sqrt{1 \text{ mH} \times 500 \text{ pF}}} = 225 \text{ kHz}$

Oscillator bandwidth $= f_H - f_L = 503 - 225 = 278 \text{ kHz}$

13.4 COLPITTS OSCILLATORS

The Colpitts oscillator is somewhat opposite to the Hartley oscillator as the centre tapping is made from capacitive voltage divider network instead of tapped inductive coil as shown in Figure 13.7. Similar to the Hartley oscillator, the tuned tank circuit consists of an *LC* resonance circuit connected between the collector and base of the transistor amplifier.

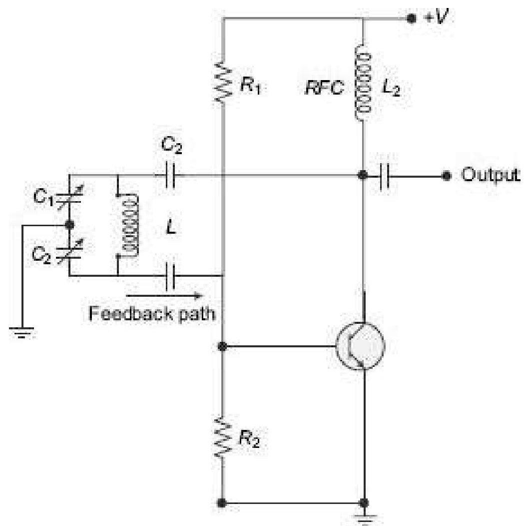

Figure 13.7 *Basic Colpitts oscillator circuit*

The emitter of the transistor amplifier is connected to the junction of capacitors C_1 and C_2 which are connected in series with the required external phase shift obtained in a similar manner to that in the Hartley oscillator. The amount of feedback is controlled by the ratio of C_1 and C_2 which are generally ganged together to provide a constant amount of feedback. Once again, the frequency of oscillations for a Colpitts oscillator is determined by the resonant frequency of the *LC* tank circuit and is given as

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

where C_T is the capacitance of C_1 and C_2 connected in series and is given as.

$$\frac{1}{C_T} = \frac{1}{C_1} + \frac{1}{C_2} \quad \text{or} \quad C_T = \frac{C_1 \times C_2}{C_1 + C_2}$$

A common emitter-amplifier configuration is employed here, with the output signal 180° out of phase with respect to the input signal. The two capacitors are connected together in series but in parallel with the inductive coil resulting in overall phase shift of the circuit being zero. Resistors R_1 and R_2 are used for the usual stabilising dc bias for the transistor in the normal manner while the capacitor acts as dc-blocking capacitors.

Example 13.2

One Colpitts oscillator circuit has two capacitors of 10 pF and 100 pF respectively connected in parallel with an inductor of 10 mH. Determine the frequency of oscillations of the circuit.

Solution The circuit consists of two capacitors in series.

So, the total capacitance is given as

$$C_T = \frac{C_1 \times C_2}{C_1 + C_2} = \frac{10\text{ pF} \times 100\text{ pF}}{10\text{ pF} + 100\text{ pF}} = 9.1\text{ pF}$$

If the inductor is of 10 mH then the frequency of oscillation is

$$f = \frac{1}{2\pi\sqrt{LC_T}} = \frac{1}{6.283\sqrt{0.01 \times 9.1 \times 10^{-12}}} = 527.8\text{ kHz}$$

Then the frequency of oscillations for the oscillator is 527.8 kHz.

13.5 THE *RC* OSCILLATOR

So far, only *LC* tuned circuits that cause phase shift of 180° due to inductive or capacitive coupling in addition to a 180° phase shift produced by the transistor or op-amp, have been discussed. Such *LC* oscillators are employed to generate high-frequency oscillations but they cannot be employed for generation of low frequency oscillations as they become too bulky and expensive. *RC* oscillators are commonly used for generating audio-frequencies as they provide good frequency stability and waveform. When an *RC* network is connected in class-A configuration, a single stage amplifier will produce 180° of phase shift between its output and input signals. If an oscillator has to oscillate a sufficient positive feedback of the correct phase must be provided with the amplifier being used as an inverting stage to achieve this. In an *RC* oscillator, the input is shifted 180° through the amplifier stage and 180° again through a second inverting stage giving 360° (180° + 180°) of phase shift which is the same as 0° thereby providing the required positive feedback. This method of phase shift between the input to an *RC* network and the output from the same network is employed in a resistance-capacitance oscillator or simply an *RC* oscillator.

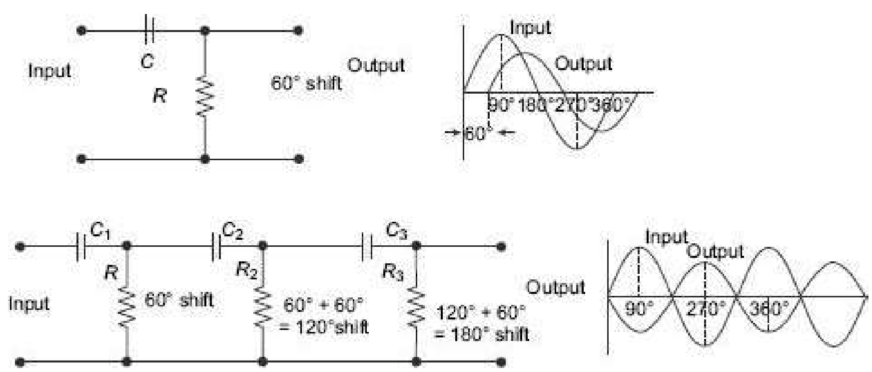

Figure 13.8 *RC phase-shift network*

In Figure 13.8, the circuit on the top shows a single resistor-capacitor network and whose output voltage leads the input voltage by some angle less than 90°. An ideal *RC* circuit would produce a phase shift of exactly 90°, as it is known that the amount of actual phase shift in the circuit depends upon the values of the resistor, capacitor and the chosen frequency of oscillations. The phase angle (**Φ**) is given as

$$\Phi = \tan^{-1}\left(\frac{R}{X_c}\right)$$

In this simple example above, the values of *R* and *C* have been chosen so that at the required frequency, the output voltage leads the input voltage by an angle of about 60°.

Then by cascading or connecting together three such *RC* networks in series, it is possible to produce a total phase shift in the circuit of 180° at the chosen frequency and it forms the basis of an *RC* oscillator circuit. It is known that in an amplifier circuit, either using a BJT or Op-AMP, it will produce a phase-shift of 180° between its input and output. If an *RC* phase-shift network is connected between this input and output of the amplifier, the total phase shift will become 360°, i.e. the feedback is in-phase.

13.5.1 Basic *RC* Oscillator Circuit

The *RC* oscillator as shown in Figure 13.9, which is called a phase-shift oscillator, produces a sine-wave output signal using regenerative feedback from the resistor-capacitor combination.

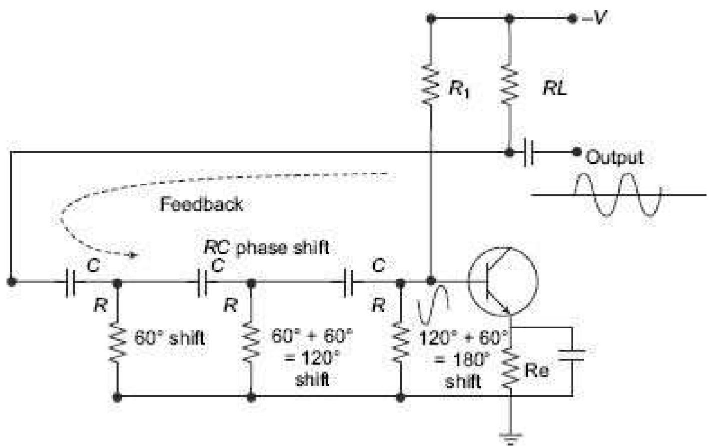

Figure 13.9 *Basic RC oscillator circuit*

This regenerative feedback from the *RC* network is possible due to the capability of the capacitor to store an electric charge. The resistor-capacitor feedback network can be connected as shown above to produce a leading phase shift or interchanged to produce a lagging phase and the outcome is still the same as the sine-wave oscillations only occur at the frequency at which the overall phase shift is 360°. By varying one or more of the resistors or capacitors in the phase-shift network, the frequency can be varied and generally this is done using a 3-ganged variable capacitor. If all the resistors *R* and the capacitors *C* are equal in value then the frequency of oscillations produced by the oscillator is given

$$f = \frac{1}{2\pi\sqrt{2N}RC}$$

where f is the output frequency in Hz, R is the resistance in ohms, C is the capacitance in farads, N is the number of *RC* stages and in our example, $N = 3$

13.5.2 The Op-amp ffCOscillator

Operational Amplifier (Op-amp) *RC* oscillators are more common than their bipolar transistor counterparts. The *RC* network that produces the phase shift is connected from the op-amps output back to its non-inverting input as shown in Figure 13.10.

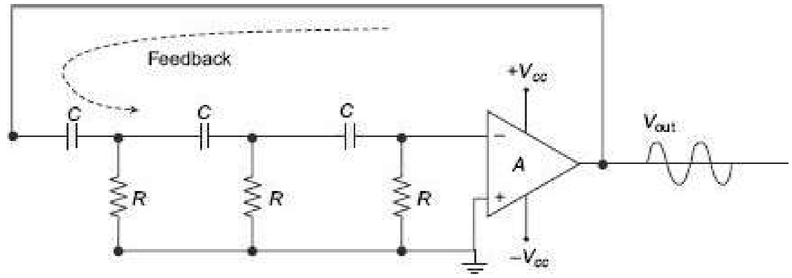

Figure 13.10 *Operational-amplifier RC oscillators*

The feedback is connected to the non-inverting input and the operational amplifier is connected in its inverting amplifier configuration which produces the required 180° phase shift. The *RC* network produces the other 180° phase shift at the required frequency. Although it is possible to cascade together two *RC* stages to provide the required 180° of phase shift, but in that case the stability of the oscillator at low frequencies is poor. One of the most important characteristics of an *RC* oscillator is its frequency stability. This is the ability of an oscillator to provide a constant frequency output under varying load conditions. So to obtain higher frequency stability, three or even four *RC* stages together are cascaded. *RC* oscillators with four stages are widely used because commonly available operational amplifiers come in quad IC packages. So, designing a 4-stage oscillator with 45° of phase shift relative to each other is comparatively easy. *RC* oscillators are stable and provide a well-shaped sine-wave output with the frequency being proportional to 1/*RC*. Using a variable capacitor, a wider frequency range is possible. However, the use of *RC* oscillators are restricted to low-frequency applications, because of their bandwidth limitations to produce the desired phase shift at high frequencies.

Example 13.3

Determine the frequency of oscillations of a RC oscillator circuit having three-stages each with a resistor and capacitor of equal values. R = 10 kΩ and C = 500 pF

Solution Here, $R = 10$ kΩ, $C = 500$ pF, $N = 3$

Therefore, the frequency of oscillation is given as

$$f = \frac{1}{2\pi\sqrt{2N}RC} = \frac{1}{2\pi\sqrt{(2\times 3)}\times 10000\times 500\times 10^{-12}} = 12995\text{ Hz} \cong 13\text{ kHz}$$

13.6 WIEN BRIDGE OSCILLATORS

The Wien bridge oscillator is another type of oscillator which uses a *RC* network in place of the conventional *LC* tuned circuit to produce a sinusoidal output waveform. The Wien bridge oscillator is a two-stage *RC* coupled amplifier circuit that has good stability at its resonant frequency, low distortion and is very easy to tune making it a popular circuit as an audiofrequency oscillator. The phase shift of the output signal is considerably different from the previous *RC* oscillators.

The Wien bridge oscillator employs a feedback circuit consisting of a series *RC* circuit connected with a parallel *RC* of the same component values producing a phase delayadvance (lag-lead) circuit depending upon the frequency as shown in Figure 13.11.

The above *RC* network is a typical second-order frequency dependent band-pass filter with high quality factor(Q). It consists of a low-pass filter (series *RC* network) and another high-pass filter (parallel *RC* network). At low frequencies, the reactance Xc of the series capacitor is very high so the series capacitor acts like an open circuit and blocks any input signal V_{in} and therefore there is no output signal V_{out}. At high frequencies, the reactance of the parallel capacitor is very low so the parallel capacitor acts like a short circuit on the output, so again there is no output signal. However, between these two extremes, the output voltage reaches a maximum and the frequency at which this happens is called the resonant frequency (f_r) as the circuit's reactance equals its resistance $X_c = R$. At this resonant frequency, the output voltage is one third (1/3) of the input voltage.

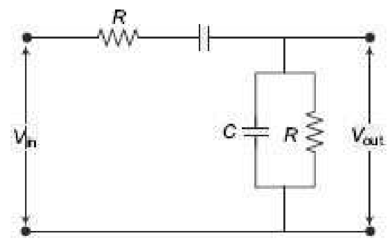

Figure 13.11 *RC phase shift network*

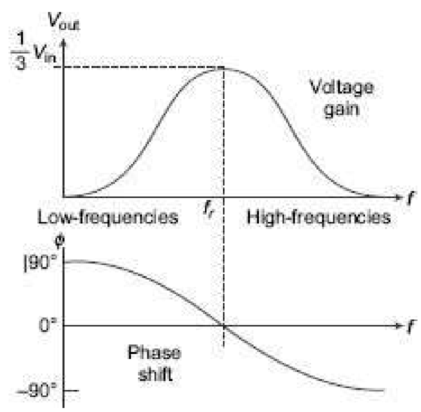

Figure 13.12 *Output gain and phase shift*

It can be seen as in Figure 13.12 that at very low frequencies, the phase angle between the input and output signals is positive, i.e. leading in nature, while at very high frequencies the phase angle becomes negative, i.e. lagging in nature. In the middle of these two points the circuit is at its resonant frequency (f_r) with the signals being in-phase or 0°. The expression of resonant frequency is as follows:

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

This frequency-selective *RC* network forms the basis of the Wien Bridge oscillator circuit. The Wien bridge oscillator circuit is produced by placing this *RC* network across a non-inverting amplifier. As in Figure 13.13, the output of the operational amplifier is fed back to the inputs in-phase with part of the feedback signal connected to the inverting input terminal via the resistor divider network of R_1 and R_2, while the other part is fed back to the non-inverting input terminal via the *RC* network. Then at the selected resonant frequency (f_r), the voltages applied to the inverting and non-inverting inputs will be equal and in-phase. So the positive feedback will cancel the negative feedback signal causing the circuit to oscillate. Also the voltage gain of the amplifier circuit should be 3 as set by the resistor network, R_1 and R_2.

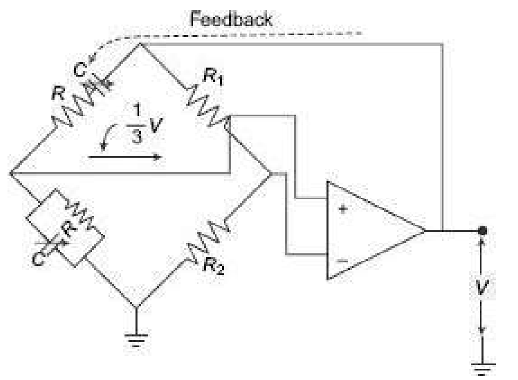

Figure 13.13 *Wien bridge oscillator with op-amp*

Example 13.4

Determine the maximum and minimum frequency of oscillations of a Wien bridge oscillator circuit having a resistor of 10 kΩ and a variable capacitor of 1 nF to 1000 nF.

Solution The frequency of oscillations for a Wien bridge oscillator is given as:

$$f_r = \frac{1}{2\pi RC}$$

Lowest frequency, $f_{min} = \dfrac{1}{2\pi(10\ \text{k}\Omega)\times(1000\times10^{-9})} = 15.9\ \text{Hz}$

Highest frequency, $f_{max} = \dfrac{1}{2\pi(10\ \text{k}\Omega)\times(1\times10^{-9})} = 15915\ \text{Hz}$

13.7 CRYSTAL OSCILLATORS

Frequency stability is the most important feature of an oscillator. Frequency stability is the ability to provide a constant frequency output under varying load conditions. Frequency stability of the output signal can be improved by proper selection of the components used for the resonant feedback circuit including the amplifier but there is a limit to the stability that can be obtained from normal *LC* and *RC* tank circuits. Some of the factors that affect the frequency stability of an oscillator include temperature, variations in the load and changes in the power supply. For very high stability, a quartz crystal is generally used as the frequency-determining device to produce a typical type of oscillator circuit known as crystal oscillators.

The crystal oscillators are implemented using the piezo-electric effect. This is actually realised when a voltage source is applied to a small thin piece of crystal quartz. The quartz crystal begins to change shape. This piezo-electric effect is the property of a crystal by which an electrical charge produces a mechanical force by changing the shape of the crystal. In reverse sense, a mechanical force applied to the crystal produces an electrical charge. This piezo-electric effect produces mechanical vibrations or oscillations which are used to replace the *LC* tank circuit and can be seen in many different types of crystal substances with the most important of these for electronic circuits being the quartz minerals because of their superior mechanical strength.

The quartz crystal is a very small, thin piece or wafer of cut quartz with the two parallel surfaces metalised to make the electrical connections in a crystal oscillator. The physical size and thickness of a piece of quartz crystal is tightly controlled since it affects the final frequency of oscillations and is called the *characteristic frequency of the crystal*. Once cut and shaped, the crystal cannot be used at any other frequency. The crystal's characteristic or resonant frequency is inversely proportional to its physical thickness between the two metalised surfaces. A mechanically vibrating crystal can be represented by an equivalent electrical circuit consisting of low resistance, large inductance and small capacitance as shown in Figure 13.14.

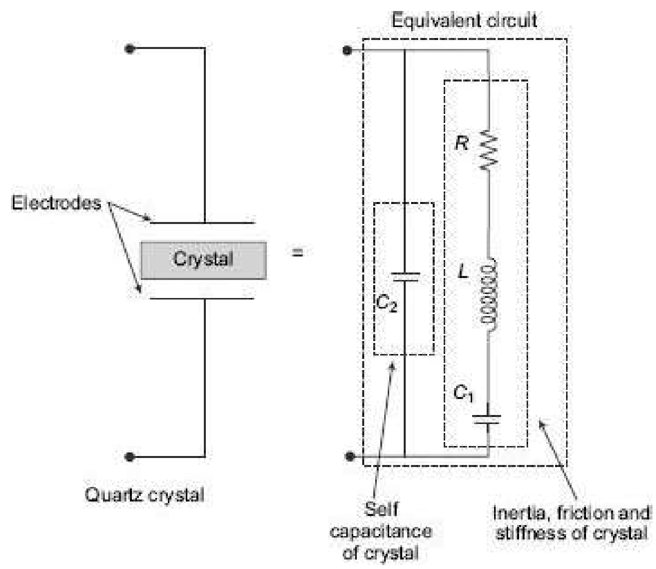

Figure 13.14 *Quartz crystal*

Like an electrically tuned tank circuit, a quartz crystal has resonant frequency with very high Q factor due to low resistance. The frequencies of quartz crystals range from 4 kHz to 10 MHz. The cut of the crystal also determines how it will vibrate and behave as some crystals will vibrate at more than one frequency. Also, if the crystal is of varying thickness, it has two or more resonant frequencies having both a fundamental frequency and harmonics such as second or third harmonics. However, usually the fundamental frequency is more pronounced than the others and this is the one used. The equivalent circuit above consists of three reactive components and there are two resonant frequencies, the lowest is a series-type frequency and the highest a parallel-type resonant frequency.

In a crystal oscillator circuit, the oscillator will oscillate at the crystal's fundamental series resonant frequency as the crystal always intends to oscillate when a voltage source is applied to it. It is also possible to tune a crystal oscillator to any even harmonic of the fundamental frequencies, (2^{nd}, 4^{th}, 8^{th}, etc.) and these are known generally as harmonic oscillators while overtone oscillators vibrate at odd multiples of the fundamental frequencies, (3^{rd}, 5^{th}, 11^{th}, etc). Crystal oscillators that operate at overtone frequencies do so using their series resonant frequency.

13.7.1 Colpitts Crystal Oscillator

The design of a Colpitts crystal oscillator is very similar to the Colpitts oscillator. The *LC* tank in the Colpitt oscillator circuit has been replaced by a quartz crystal as shown below in Figure 13.15. The input signal to the base of the transistor is inverted at the transistors output. The output signal at the collector is then taken through 180° phase shifting network which contains the crystal operating in a series resonant mode.

The output is fed back to the input which is inphase with the input providing the necessary positive feedback. Resistors R_1 and R_2 bias the transistor in class-A operation and the resistor R_e is taken so that the loop gain is slightly higher than unity. Capacitors C_1 and C_2 are made as large as possible in order to get the frequency of series resonant mode of the crystal.

This frequency does not depend upon the values of these capacitors. The circuit diagram above of the Colpitts crystal oscillator circuit shows that capacitors C_1 and C_2 shunt the output of the transistor which reduces the feedback signal. Therefore, the gain of the transistor limits the maximum values of C_1 and C_2. Another important point is that the output amplitude should be kept low in order to avoid excessive power dissipation in the crystal, otherwise, the crystal could destroy itself by excessive vibration.

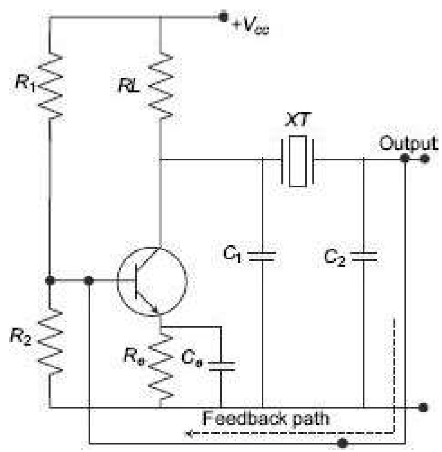

Figure 13.15 *Colpitts crystal oscillator*

13.8 PIERCE OSCILLATOR

The Pierce oscillator is another common design of a crystal oscillator. It uses the crystal as part of its feedback path instead of the resonant tank circuit. A JFET is used as amplifier as it provides a very high input impedance with the crystal connected between the drain (output) terminal and the gate (input) terminal as shown in Figure 13.16.

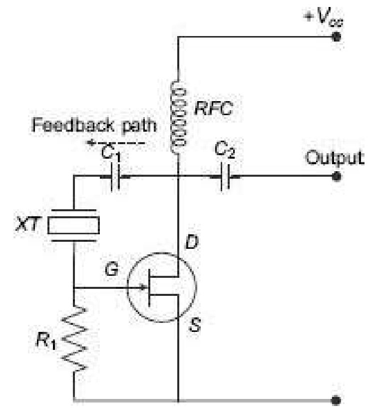

Figure 13.16 *Pierce crystal oscillator*

In the above circuit, the crystal determines the frequency of oscillations and operates on its series resonant frequency giving a low-impedance path between output and input. It gives 180° phase shift at resonance and makes the feedback positive. The maximum voltage range at the drain terminal sets the amplitude of the output sine wave. Resistor R_1 regulates the amount of feedback and crystal drive. The voltage across the Radio Frequency Choke (RFC) reverses during each cycle. The Pierce oscillator can be implemented using the minimum number of components. Because of this, Pierce oscillators are used to design most digital clocks, watches and timers, etc.

13.9 MICROPROCESSOR CLOCKS

The crystal quartz oscillator is the most suitable frequency-determining device in virtually all microprocessors, microcontrollers, PICs and CPUs, used to generate their clock waveforms. Crystal oscillators provide the highest accuracy and frequency stability compared to resistor-capacitor or inductor-capacitor oscillators. The CPU clock dictates how fast the processor can process the data, and a microprocessor having a clock speed of 3 MHz means that it can process data internally 3 million times a second at every clock cycle. Generally, all that is needed to produce a microprocessor clock waveform is a crystal and two ceramic capacitors of values ranging between 15 to 33 pF as shown in Figure 13.17.

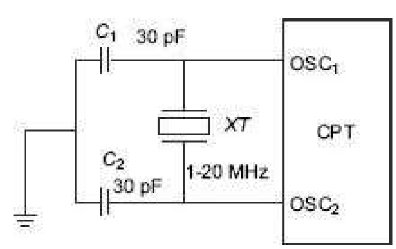

Figure 13.17 *Microprocessor oscillator*

Most microprocessors, microcontrollers and PICs have two oscillator pins labelled OSC_1 and OSC_2 to connect to an external quartz crystal, *RC* network or even a ceramic resonator. In this application, the crystal oscillator produces a train of continuous square-wave pulses whose frequency is controlled by the crystal which in turn executes the instructions that control the device.

Table 13.1 *Oscillators with their operating frequency range*

Type of oscillator	*Approximate frequency range*
Crystal oscillator	Fixed frequency
Wien bridge oscillator	1 Hz to 1 MHz
Phase-shift oscillator	1 Hz to 10 MHz
Hartley oscillator	10 kHz to 100 MHz
Colpitts oscillator	10 kHz to 100 MHz

13.10 SQUARE WAVE AND PULSE GENERATORS

Wave shape, or wave profile, of a single pulse is shown in Figure 13.18. The characteristics of a single pulse are given below.

- The voltage rises very rapidly from zero to its maximum value.
- It stays steady at the maximum value for a time.
- It then falls very rapidly back to zero.
- The duration of a pulse can be anywhere from a very long time (days) to a very short time (picoseconds or less).
- Pulses do not rise and fall instantaneously but take time (which may be very short).
- They are called the rise and fall times.

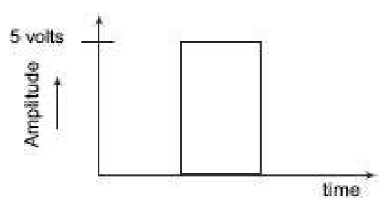

Figure 13.18 *Wave shape of a single-pulse*

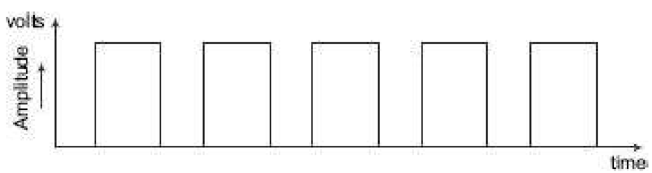

Figure 13.19 *Waveform of pulse train*

As shown in Figure 13.19, a few characteristics of pulse trains are stated below:

- If pulses occur one after another, they are called a pulse train.
- The duration time of a pulse is called the *mark.*
- The time between pulses is called the *space*.
- The relative times are expressed as the *mark-to-space ratio.*
- Mark to space ratios may vary.

13.10.1 Typical Square Wave Generator

A continuous signal with regular wave shape is one requirement in a wide range of applications. One of the most important of these is a square-wave generator.

The circuit in Figure 13.20 uses an op-amp as comparator with both positive and negative feedback to control its output voltage. Because the negative feedback path uses a capacitor while the positive feedback path does not, there is a time delay before the comparator is triggered to change state. As a result, the circuit oscillates, or keeps changing state back and forth at a predictable rate.

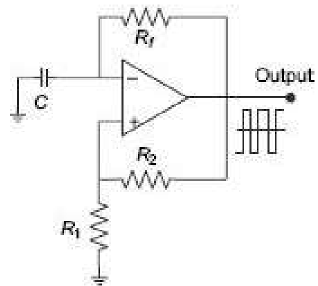

Figure 13.20 *Square wave generator circuit using op-amp*

Since no force or excitation is given to limit the output voltage, it will switch from one extreme to the other. If it is assumed that output voltage starts at −12 volts then the voltage at the positive or non-inverting input terminal will be set by R_2 and R_1 to a Figure 13.20 fixed voltage equal to $-12\ R_1/(R_1 + R_2)$ volts. Now, it becomes the reference voltage for the comparator, and the output will remain unchanged until the negative or inverting input terminal becomes more negative than this value. But the inverting terminal is connected to a capacitor (C) which is gradually charging in a negative direction through the resistor R_f. Since C is charging towards −12 volts, but the reference voltage at the non-inverting input is necessarily smaller than the−12 volt limit, eventually the capacitor will charge to a voltage that exceeds the reference voltage. When that happens, the circuit will immediately change state. The output will become +12 volts and the reference voltage will abruptly become positive rather than negative. Now the capacitor will charge towards +12 volts, and the other half of the cycle will take place. The output frequency is given by the approximate equation:

$$f_{out} = \frac{1}{2R_f C \ln\left(\frac{2R_1}{R_2}+1\right)}$$

In the practical field, the circuit-component values are chosen such that R_1 is approximately $R_f/3$, and R_2 is in the range of 2 to 10 times R_1.

13.10.2 OP-AMP Astable Multivibrator and Monostable Multivibrator Circuits

Relaxation oscillators are normally non-sinusoidal waveform generators. The relaxation oscillator using an op-amp shown in Figure 13.21 is a square-wave generator. Square waves are relatively easy to generate.

The frequency of oscillation of a circuit is dependent on the charging and discharging of a capacitor C through the feedback resistor R_f. The main component of the oscillator is an inverting op-amp working as comparator. A comparator circuit has positive feedback which increases the gain of the amplifier. A comparator circuit having positive feedback offers two advantages.

First, the high gain causes the op-amp's output to switch very quickly from one state to another and vice versa. Second, the use of positive feedback gives the hysteresis loop in the circuit operation.

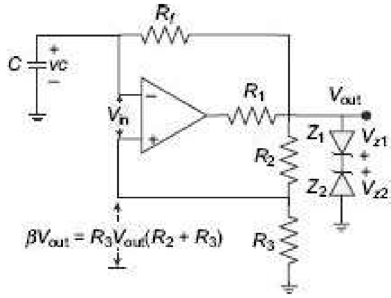

Figure 13.21 *Op-amp square-wave generator*

As shown in Figure 13.21, in the op-amp square-wave generator, the output voltage V_{out} is connected to ground through two Zener diodes Z_1 and Z_2, connected back-to-back and is limited to either $\boldsymbol{V_{Z2}}$ or V_{Z1}. A fraction of the output is fed back to the non-inverting (+) input terminal. A combination of R_f and C act as a low-pass RC circuit which is used to integrate the output voltage V_{out} The capacitor voltage V_c is applied to the inverting input terminal instead of external signal.

At that point of time, the differential input voltage is given as $V_{\text{in}} = V_c - \beta V_{\text{out}}$.

When V_{in} is + ve $V_{\text{out}} = -\, V_{\text{zl}}$

and when V_{in} is −ve , $V_{\text{out}} = +\, V_{\text{z2}}$.

Consider an instant when $V_{\text{in}} < 0$. At this instant, $V_{\text{out}} = +V_{z2}$, and the voltage at the non-inverting (+) input terminal is βV_{z2}, the capacitor C charges exponentially towards V_{z2}, with a time constant R_fC. The output voltage remains constant at V_{z2} until v_c equal βV_{z2}. When it happens, comparator output reverses to $-V_{z1}$. Now v_c changes exponentially towards $-V_{z1}$ with the same time constant and again the output makes a transition from $-V_{z1}$ to $+\, V_{z2}$ when V_c equals $-\beta V_{z1}$

Let $V_{z1} = V_{z2}$

The time period, T of the output square wave is determined using the charging and discharging phenomena of the capacitor C. The voltage across the capacitor V_c when it is charging from $-B\, V_z$ to $+\, V_z$ is given by

$$V_{\text{c}} = [1 - (1 + \beta)]e^{-T/2\tau}$$

where $\tau = R_fC$

The waveforms of the capacitor voltage v_c and output voltage V_{out} (or v_z) are shown in Figure 13.22.

When $t = t/2$,

$$V_c = +\beta V_z \text{ or } +\beta V_{\text{out}}$$

Therefore, $\beta V_z = V_z [1 - (1 + \beta)e^{-T/2\tau}]$

or $e^{-T/2\tau} = (1 - \beta)/(1 + \beta)$

or $T = 2\tau \log_e [(1 - \beta)/(1 + \beta)] = 2R_{fc} \log_e [1 + (2R_3/R_2)]$

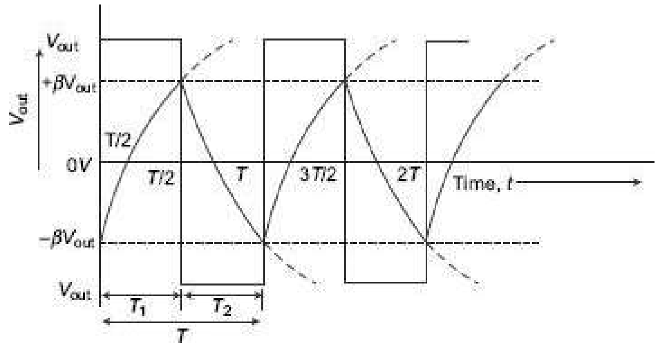

Figure 13.22 *Output and capacitor voltage waveforms*

Here, the frequency ($f = 1/T$), of the square wave is independent of the output voltage V_{out}. This circuit is also known as free-running or astable multivibrator. This circuit has two quasi-stable states as shown in Figure 13.22. The output remains in one state for the time T_1 and then a rapid transition to the second state and remains in that state for time T_2. The cycle repeats itself after time $T = (T_1 + T_2)$. where, T is the time period of the square-wave. The op-amp square-wave generator offers good performance in the frequency range of about 10 Hz − 10 kHz. But, at higher frequencies, the slew rate of the op-amp limits the slope of the output square wave. The matching of two Zener diodes Z_1 and Z_2 decides symmetry of the output waveform. The unsymmetrical square wave (T_1 not equal to T_2) can be obtained by choosing different charging time constants for charging the capacitor C to + V_{out} and $-V_{out}$

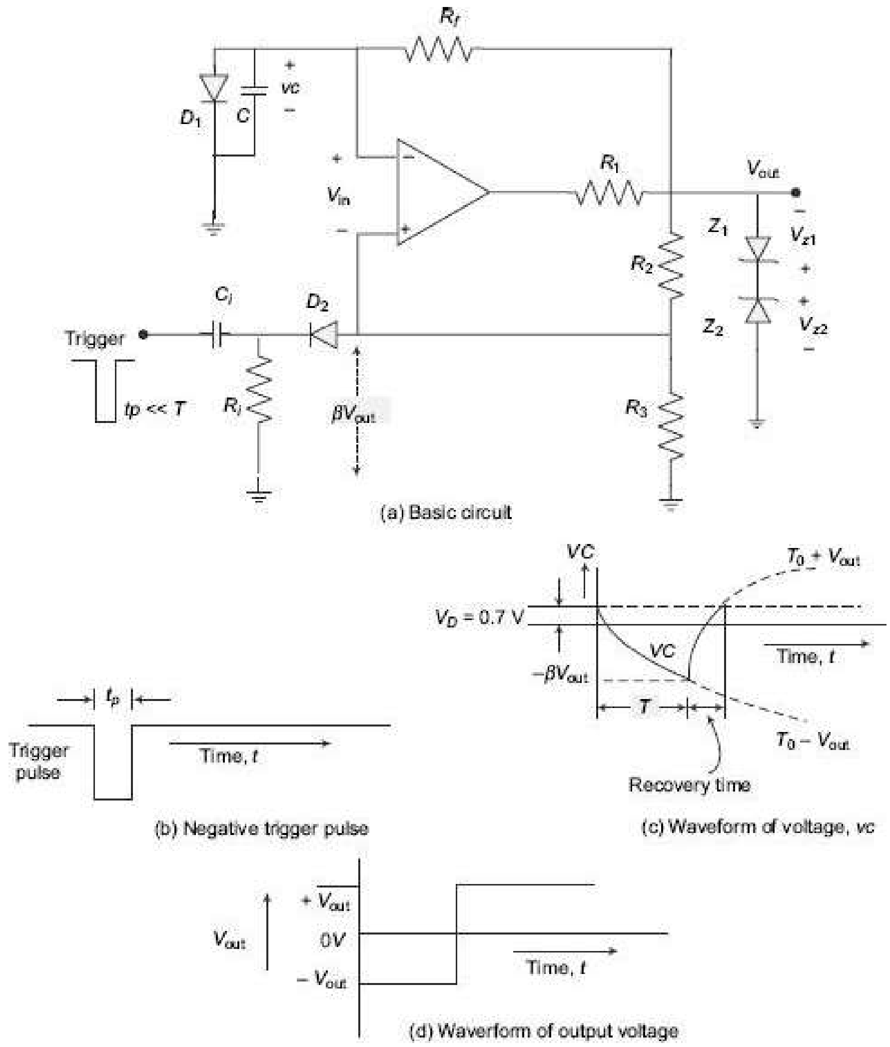

Figure 13.23 *Pulse generator/monostable circuit and waveforms*

A pulse generator circuit, as shown in Figure 13.23, is a monostable multivibrator A Monostable Multi Vibrator (MMV) has one stable state and one quasi-stable state. An external triggering pulse pushes the circuit to operate in the quasi-stable state from the stable state. The circuit comes back to its stable state after a time period T. As a result, a single output pulse is generated in response to an input pulse and is referred to as a *one-shot* or *mono shot.* The monostable multivibrator circuit shown in Figure 13.23. is obtained by modifying the previous circuit by connecting a diode D_1 across the capacitor C so as to clamp v_c at v_d during positive excursion.

At steady state, the circuit will remain in its stable state and the output will be $V_{OUT} = +V_{OUT}$ or $+ V_z$. The capacitor C is clamped at the voltage V_D (= 0.7 V). The voltage V_D must be less than βV_{OUT} for $V_{in} < 0$. The circuit can be switched to the other state by applying a negative pulse with amplitude greater than $\beta V_{OUT} - V_D$ to the non-inverting (+) terminal of the op-amp. If a trigger pulse with amplitude greater than $\beta V_{OUT} - V_D$ is given, V_{in} goes positive causing a transition in the state of the circuit to $-V_{out}$. The capacitor C starts charging exponentially with a time constant of $\tau = R_f C$ towards V_{OUT} and diode D_1 becomes reverse-biased. When the capacitor voltage v_c becomes more negative than $-\beta V_{OUT}$, V_{in} becomes negative and, therefore, the output swings back to $+ V_{OUT}$ which is the steady-state output. The capacitor now charges towards + V_{OUT} till v_c attains V_D and capacitor C becomes clamped at V_D. The trigger pulse, capacitor voltage waveform and output voltage waveform are shown in Figure 13. 23(b), 23(c) and 23(d) respectively.

The trigger pulse width T must be much smaller than the duration of the output pulse generated, i.e. $T_P = T$ and for reliable, operation the circuit should not be triggered again before T.

During the quasi-stable state, the exponential profile of the capacitor voltage is expressed as,

$$v_c = -V_{OUT} + (V_{OUT} + V_D)e^{-t/\tau}$$

At, $t = T$, $\quad v_c = -\beta V_{OUT}$

So $\quad -\beta V_{OUT} = -V_{OUT} + (V_{OUT} + v_D)\, e^{-T/\tau}$

or, $\quad T = R_f C \log_e (1 + V_D/V_{out})/ 1 - \beta$

Normally, $V_D << V_{OUT}$ and taking $R_2 = R_3$

The factor, $\quad \beta = R_3/(R_2 + R_3) = 1/2$

So, $\quad T = R_f C \log_e 2 = 0.693\, R_f\, C$

13.11 TRIANGULAR WAVE GENERATOR

Simply integrating the generated square wave can produce a triangular wave. With the basic squarewave-generator circuit, if a gradually charging capacitor is used to set the timing or frequency of the circuit then the desired triangular signal may be obtained. Since the capacitor is charging through a resistor, the charging profile necessarily follows a logarithmic curve, rather than a linear ramp.

As shown in Figure 13.24, in the right part of the circuit, a separate integrator is used to generate a ramp voltage from the generated square wave. As a result, both waveforms from a single circuit can be obtained. Note that the integrator inverts as well as integrating, so it will produce a negative-going ramp for a positive input voltage, and vice versa.

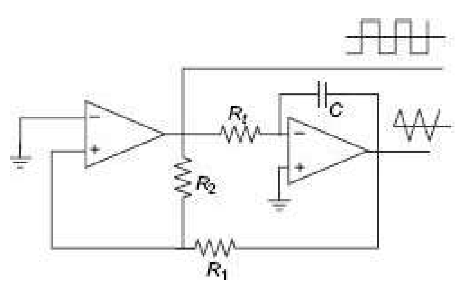

Figure 13.24 *Triangular wave generator*

Since an op-amp is in use in the integrator, to get the triangle wave, a logarithmic response is not obtained anywhere in the circuit. As a result, the equation for the operating frequency is

$$f_{out} = \frac{1}{4R_fC}\left(\frac{R_2}{R_1}\right)$$

The square-wave amplitude is still the limit of voltage transition, which are assuming here to be ±12 volts. The triangle wave's amplitude is set by the ratio of R_1/R_2.

The circuit shown in Figure 13.25 is an example of a relaxation oscillator designed with two op-amps. The integrator output waveform will be triangular if the input to it is a square wave. So, a triangular-wave generator can be formed by simply cascading an integrator and a square-wave generator, as illustrated in Figure 13.13.25(a). To implement the circuit, a dual op-amp, two capacitors, and at least five resistors are required. The rectangular-wave output swings between $+V_{sat}$ and $-V_{sat}$ with a time period determined. The frequency of triangular-waveform and the square waveform are same.

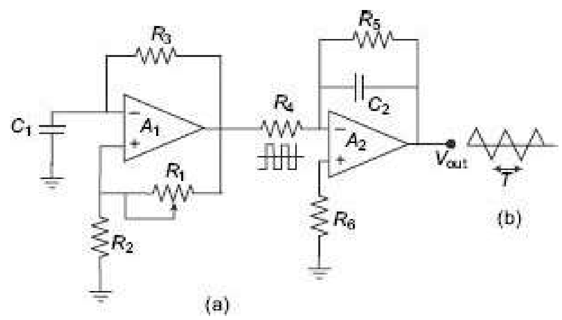

Figure 13.25 *Basic circuit of triangular-wave generator*

The input to the integrator A_2 is a square wave and its output is a triangular waveform, the output of the integrator will be a triangular wave only when $R_4\ C_2 > T/2$; where T is the time period of the square wave. As a general rule, R_4C_2 should be equal to T. To obtain a stable triangular wave, it may also be necessary to shunt the capacitor C_2 with resistance $R_5 = 10\ R_4$ and connect an offset volt compensating network at the non-inverting (+) input terminal of the op-amp A_2. As usual, the frequency of the triangular-wave generator is limited by the op-amp slew rate. It is better to use a high slew rate op-amp (like LM 301), to generate triangular waveforms of relatively higher frequency.

With fewer components, another triangular-waveform generator can be formed and the circuit of that is shown in Figure 13.26(a). The arrangement consists of a Schmitt trigger in non-inverting configuration followed by an integrator. The rectangular wave output of the Schmitt trigger drives an integrator. The integrator generates a triangular wave, which is fed back and used to drive the Schmitt trigger. Thus, the first part of the circuit drives the second part of the circuit, and the second drives the first. But the question arises on how the circuit gets started at the outset. This part is explained as follows.

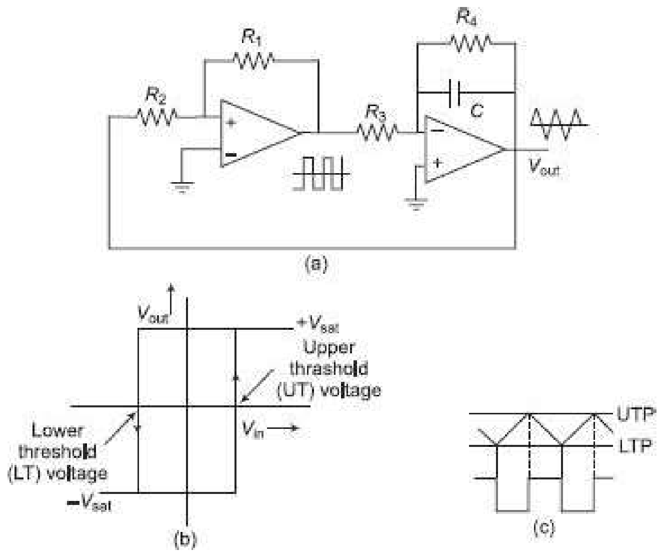

Figure 13.26 *(a) Feedback circuit with Schmitt trigger and integrator producing triangular output waveform (b) Transfer characteristic of Schmitt trigger (c) Output waveforms*

The fact is that the moment the Schmitt trigger is connected to power supplies, the output of the Schmitt trigger must be either at low state or at high state. If the Schmitt trigger output is low then the output of the integrator will be a rising ramp and for Schmitt trigger of high output, the integrator will produce a falling ramp. In any case, the triangular waveform will start to generate, and the positive feedback to the Schmitt trigger input keeps it going. The transfer characteristic of the Schmitt trigger is shown in Figure 13.26(b). When the output is low, the input must increase to the upper threshold voltage to switch the output to high. Likewise, when the output is high, the input must fall to the lower threshold voltage to switch the output to low. The triangular wave produced by the integrator is capable of driving the Schmitt trigger. When the output of the Schmitt trigger is low, the integrator develops a rising ramp which increases till it reaches the upper threshold voltage, as illustrated in Figure 13.26(c). At this point, the output of the Schmitt trigger switches to the high state and forces the triangular wave to reverse in direction. The negative or falling ramp produced by the integrator now falls till it reaches the upper threshold voltage, where another Schmitt output change occurs.

13.12 SINE WAVE GENERATOR

The demand of sine waves in many electronic applications is very high. The circuit, shown in Figure 13.27 is the scheme to implement a mathematical relationship between the sine and cosine trigonometric functions. By integrating a sine wave, an inverted cosine wave is obtained. A cosine waveform is actually the same waveform as the sine wave but shifted 90° in phase. If that cosine wave is integrated and another 90° phase shift is achieved, it produces a negative sine wave. Of course, each op-amp integrator introduces an inversion as well, so the output of the first integrator is actually a non-inverted cosine wave. This is reversed again by the second integrator, so its output is still a negative sine wave. By inverting the negative sine wave, the original sine wave can be restored.

In this circuit, R_1 is adjusted to ensure that oscillations start and to help set the output amplitude. The Zener diodes serve to limit the output signal amplitude by limiting the gain of the cosine amplifier beyond the desired level. This prevents the circuit from amplifying the signal beyond its ±12 volt limits.

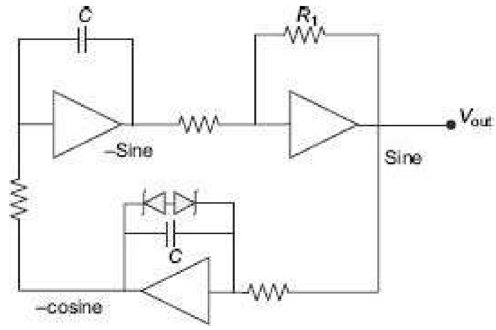

Figure 13.27 *A sine-wave generator circuit*

The clipping effect caused by the Zener diodes does introduce some distortion, but with a reasonable setting of R_1 this effect is very slight, and the distortion it causes will be significantly reduced by the second integrator.

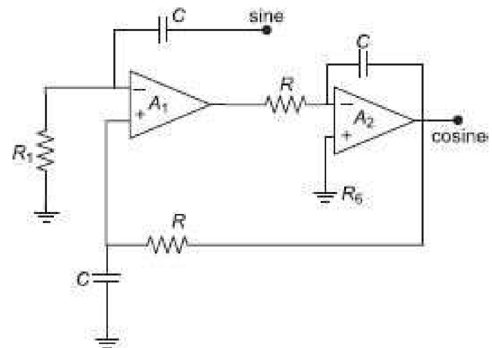

Figure 13.28 *A sine-wave oscillator*

A classic oscillator circuit is shown in Figure 13.28. In this circuit, the op-amp offsets must be precisely balanced; otherwise, they will accumulate on the two integrators and gradually damp out the oscillations. This circuit can be implemented nicely using a dual op amp such as the 1458. All three capacitors are the same, and R_t is taken very slightly less than R to ensure that the oscillations start the moment power is applied. Here, the frequency of oscillations is $f = 1/2\pi RC$. The frequency response of the op amps in use determines the maximum frequency of oscillations. In the circuit, the loop gain will decrease as frequency increases, and oscillations cannot be sustained if the loop gain is less than 1. The loop gain of this circuit must be greater than 1 to ensure oscillations. This circuit will also tend to clip the output waveforms. However, the same double-Zener clipping scheme in the circuit can be applied to the cosine integrator, to limit the signal amplitude and prevent either op amp from getting saturated.

As both sine and cosine waves are available, this circuit is also known as a *quadrature oscillator.*

13.13 FUNCTION GENERATORS

A function generator is a signal source that has the capability of producing different types of waveforms as its output signal. The most common output waveforms are sine waves, triangular waves square waves and sawtooth waves. The frequencies of such waveforms may be adjusted from a fraction of a hertz to several hundred kilohertz.

Actually, the function generators are very versatile instruments as they are capable of producing a wide variety of waveforms and frequencies. In fact, each of the waveforms they generate are particularly suitable for a different group of applications. The uses of sinusoidal outputs and square-wave outputs have already been described in the earlier Sections. The triangular-wave and sawtooth wave outputs of function generators are commonly used for those applications which need a signal that increases (or reduces) at a specific linear rate. They are also used in driving sweep oscillators in oscilloscopes and the *X*-axis of *X*-*Y* recorders.

Many function generators are also capable of generating two different waveforms simultaneously (from different output terminals, of course). This can be a useful feature when two generated signals are required for a particular application. For instance, by providing a square wave for linearity measurements in an audio-system, a simultaneous sawtooth output may be used to drive the horizontal deflection amplifier of an oscilloscope, providing a visual display of the measurement result. For another example, a triangular wave and a sine wave of equal frequencies can be produced simultaneously. If the zero crossings of both the waves are made to occur at the same time, a linearly varying waveform is available which can be started at the point of zero phase of a sine wave.

Another important feature of some function generators is their capability of phase locking to an external signal source. One function generator may be used to phase lock a second function generator, and the two output signals can be displaced in phase by an adjustable amount. In addition, one function generator may be phase locked to a harmonic of the sine wave of another function generator. By adjustment of the phase and the amplitude of the harmonics, almost any waveform may be produced by the summation of the fundamental frequency generated by one function generator and the harmonics generated by the other function generator. The function generator can also be phase locked to an accurate frequency standard, and all its output waveforms will have the same frequency, stability and accuracy as the standard.

The block diagram of a function generator is given in Figure 13.29. In this instrument, the frequency is controlled by varying the magnitude of current that drives the integrator. This instrument provides different types of waveforms (such as sinusoidal, triangular and square waves) as its output signal with a frequency range of 0.01 Hz to 100 kHz.

The frequency-controlled voltage regulates two current supply sources. The current supply source 1 supplies constant current to the integrator whose output voltage rises linearly with time. An increase or decrease in the current increases or reduces the slope of the output voltage and thus, controls the frequency.

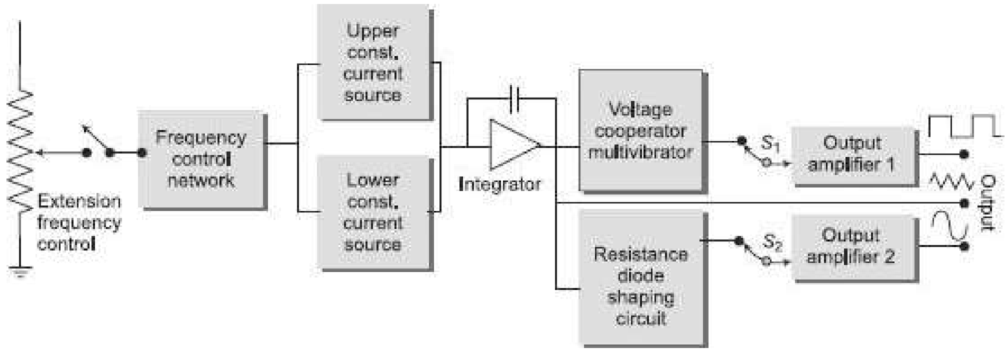

Figure 13.29 *Function generator block diagram*

The voltage comparator multivibrator changes state at a predetermined maximum level, of the integrator output voltage. This change cuts off the current supply from the supply source 1 and switches to the supply source 2. The current supply source 2 supplies a reverse current to the integrator so that its output drops linearly with time. When the output attains a predetermined level, the voltage comparator again changes state and switches on to the current supply source. The output of the integrator is a triangular wave whose frequency depends on the current supplied by the constant-current supply sources. The comparator output provides a square wave of the same frequency as the output. The resistance diode network changes the slope of the triangular wave as its amplitude changes and produces a sinusoidal wave with less than 1% distortion.

Voltage-controlled Oscillator

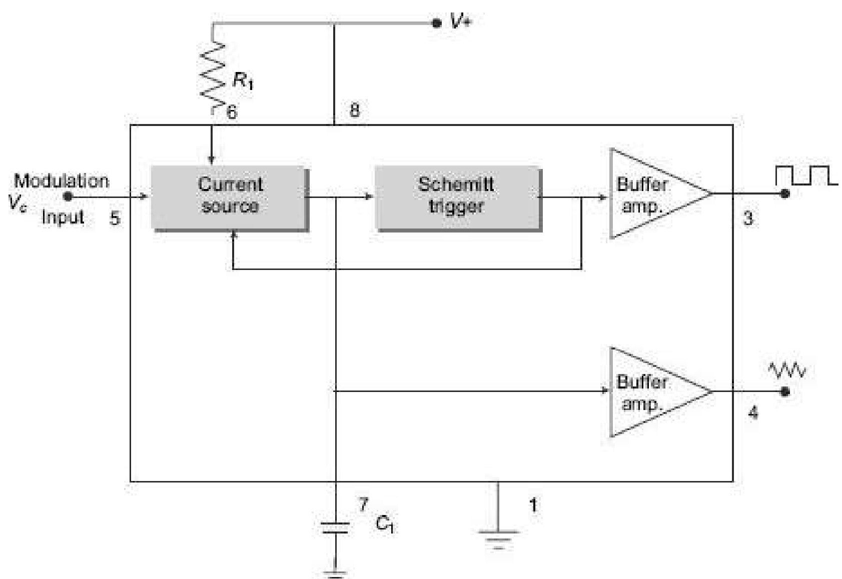

Figure 13.30 *block diagram of voltage-controlled oscillator*

In most cases, the frequency of an oscillator is determined by the time constant *RC*. However, in cases or applications such as FM, tone generators, and Frequency-Shift Keying (FSK), the frequency is to be controlled by means of an input voltage, called the control voltage. This can be achieved in a Voltage-Controlled Oscillator (VCO). A VCO is a circuit that provides an oscillating output signal (typically of square wave or triangular waveform) whose frequency can be adjusted over a range by a dc voltage. An example of a VCO is the 566 IC unit as shown in Figure 13.30 which provides simultaneously the square-wave and triangular-wave outputs as a function of input voltage. The frequency of oscillation is set by an external resistor R_1 and a capacitor C_1 and the voltage V_c applied to the control terminals. Figure 13.20 shows that the 566 IC unit contains current sources to charge and discharge an external capacitor C_v at a rate set by an external resistor R_1 and the modulating dc input voltage. A Schmitt trigger circuit is employed to switch the current sources between charging and discharging the capacitor, and the triangular voltage produced across the capacitor and square wave from the Schmitt trigger are provided as outputs through buffer amplifiers. Both the output waveforms are buffered so that the output impedance of each is 50 f_2. The typical magnitude of the triangular wave and the square wave are 2.4 $V_{\text{peak.to-peak}}$ and 5.4 $V_{\text{peak.to.peak.}}$

The frequency of the output waveforms is approximated by

$$f_{\text{out}} = 2(V^+ - V_c)/R_1C_1V^+$$

13.14 RF SIGNAL GENERATOR

An RF oscillator is employed for generating a carrier waveform whose frequency can be adjusted typically from about 100 kHz to 30 MHz. Carrier wave frequency can be varied and indicated with the help of a range selector switch and a vernier dial setting. Range is selected by employing frequency dividers. Frequency stability of the oscillator is kept very high at all frequency ranges.

- The following measures are taken in order to achieve stable frequency output.
- Frequency of output voltage changes with the change in supply voltage so regulated power supply is used.
- Buffer amplifiers are used to isolate the oscillator circuit from output circuit so that any change in the circuit connected to the output does not affect the frequency and amplitude of the oscillator output.
- Temperature also causes change in oscillator frequency, so temperature-compensating devices are used.
- *Q*-factor of the *LC* circuit should be very high, say above 20,000. This can be achieved by employing quartz crystal oscillator in place of the *LC* oscillator.
- An audio-frequency modulating signal is generated in another very stable oscillator, called the *modulation oscillator.* Provision is made in the modulation oscillator for changing the frequency and the amplitude of the signal being generated.

In this oscillator, provision is also made to get various types of waveforms such as the square, triangular waves or pulses. The radio-frequency and the modulation-frequency signals are fed to a wide-band amplifier, called the output amplifier. Percentage of modulation (can also be adjusted and it is indicated by the meter.

Modulation level can be adjusted up to 95% by a control device. The output of the amplifier is then fed to an attenuator and finally the signal goes to the output of signal generator. The output meter is provided to read the final output signal.

The accuracy to which the frequency of the RF oscillator is known is an important specification of the signal generator performance. Most laboratory-type models are usually calibrated to be within $0.5 - 1.0\%$ of the dial setting. This accuracy is usually sufficient for most measurements. For greater accuracy, if needed, a crystal oscillator, whose frequency is known to be within 0.01% or better, may be used as an internal RF calibration source.

Another key specification of signal generators is their amplitude stability. It is very important that the amplitude of the output signal remains constant as the RF frequency is varied.

13.15 SWEEP FREQUENCY GENERATOR

A sweep frequency generator is a special type of signal generator which generates a sinusoidal output whose frequency is automatically varied or swept between two selected frequencies. One complete cycle of the frequency variation is called a sweep. The rate at which the frequency is varied can be either linear or logarithmic, depending upon the design of a particular instrument. However, the amplitude of the signal output is designed to remain constant over the entire frequency range of the sweep.

Sweep-frequency generators are primarily employed for measurement of responses of amplifiers, filters, and electrical components over various frequency bands. The frequency range of a sweep-frequency generator usually extends over three bands: 0.001 Hz−100 kHz (low frequency to audio), 100 kHz−1,500 MHz (RF range), and 1 − 200 GHz (microwave range). Performance of measurement of bandwidth over a wide frequency range with a manually tuned oscillator is a time-consuming task. With the use of a sweep-frequency generator, a sinusoidal signal that is automatically swept between two chosen frequencies can be applied to the circuit under test and its response against frequency can be displayed on an oscilloscope or *X*-*Y* recorder.

Thus, the measurement time and effort is considerably reduced. Sweep generators may also be employed for checking and repairing amplifiers used in TV and radar receivers.

The block diagram of an electronically tuned sweep frequency generator is shown in Figure 13.31

As shown in Figure 13.31, the main component of a sweep-frequency generator is a master oscillator, usually an RF type, with several operating ranges which are selected by a range switch. The frequency of the output signal of the signal generator may be varied either mechanically or electronically.

In the mechanically varied models, the frequency of the output signal of the master oscillator is varied (tuned) by a motor-driven capacitor.

In the electronically tuned models, the frequency of the master oscillator is kept fixed and a varying frequency signal is produced in another oscillator, called the Voltage Controlled Oscillator (VCO). The VCO contains an element whose capacitance depends upon the voltage applied across it. This element is employed for varying the frequency of the sinusoidal output of the VCO. The output of the VCO is then combined with the output of the master oscillator in a special electronic device, called the *mixer.* The output of the mixer is sinusoidal, whose frequency depends on the difference of frequencies of the output signals of the master oscillator and VCO. For example, if the master oscillator frequency is fixed at 10.00 MHz and the variable frequency is varied between 10.01 MHz to 35 MHz, the mixer will give sinusoidal output whose frequency is swept from 10 kHz to 25 MHz.

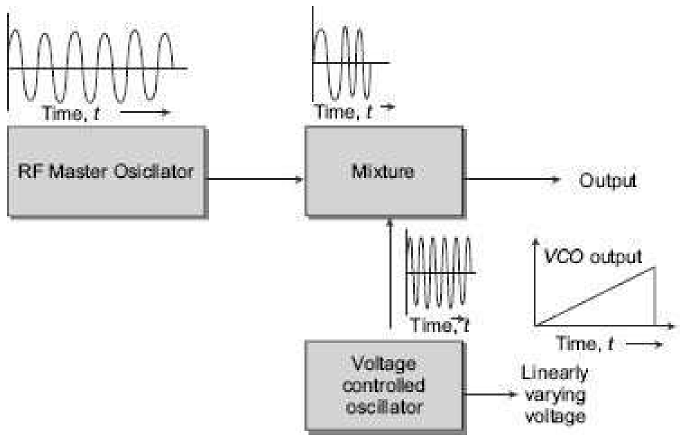

Figure 13.31 *Electronically tuned sweep generator*

The sweep rates of sweep frequency generators can be adjusted to vary from 100 to 0.01 seconds per sweep. A voltage varying linearly or logarithmically according to sweep rate can be used for driving the *X*-axis of an oscilloscope or *X*-*Y* recorder synchronously. In the electronically tuned sweep generators, the same voltage which drives the VCO serves as this voltage.

The frequency of various points along the frequency-response curve can be interpolated from the values of the end frequencies if it is known how does the frequency vary (i.e. linearly or logarithmically).

A basic system for the sweep generator is shown in Figure 13.32. A low-frequency sawtooth wave is generated from some form of oscillator or waveform generator. The instantaneous voltage of the sawtooth wave controls the frequency of an RF oscillator with its centre frequency set at the centre frequency of the device under test (filter or IF channel etc). Over a single sweep of frequency, RF output voltage from the device, as a function of time, is a plot of the filter response. By rectifying and RF filtering in a simple AM detector, the output is converted to a dc voltage varying as a function of time and this voltage is applied to the vertical input of the CRO. By synchronising the sweep of the CRO with the sawtooth output, the device response is plotted on the CRO screen.

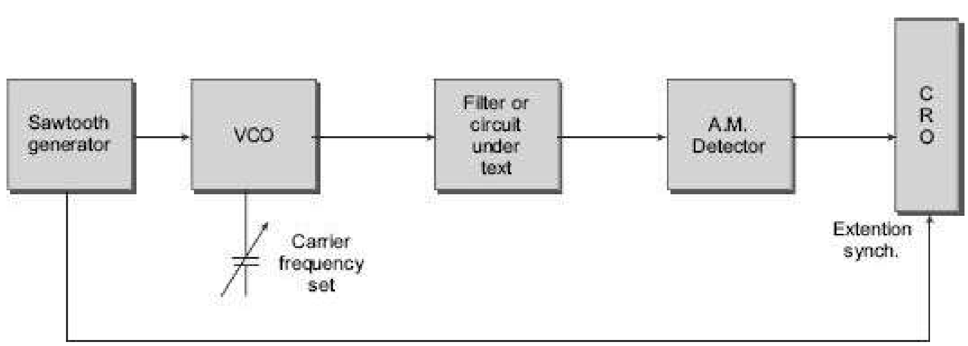

Figure 13.32 *Basic sweep-generator arrangement*

To achieve this for a range of frequencies, it is easiest to sweep a single frequency (say 1 MHz) and heterodyne this to the test frequency required. The system developed is shown in the block diagram of Figure 13.32. A 1 MHz oscillator is frequency modulated by the output of a sawtooth generator operating at 33 Hz. The modulated output is beat with an external signal generator set to provide the difference frequency centreed at the centre frequency of the filter or IF circuit under test. The output of circuit under test is fed to a simple AM detector which provides varying dc output level to feed the CRO vertical input. By synchronising the CRO sweep circuit to the 33 Hz sweep generator, a plot of test circuit response is displayed in terms of amplitude versus frequency.

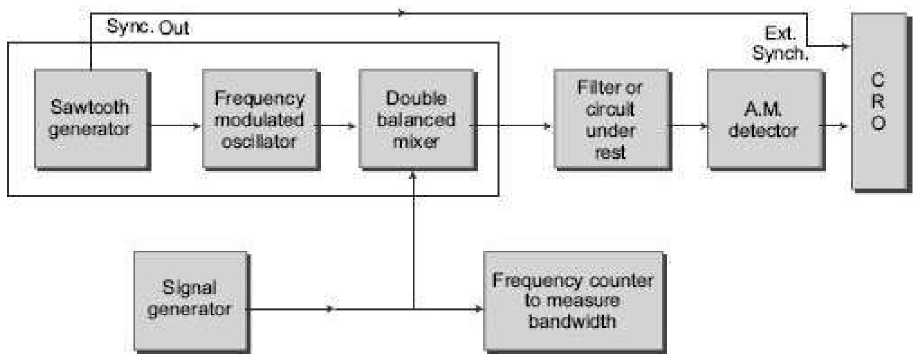

Figure 13.33 *The heterodyne sweep generator system—sweep frequency width is independent of output frequency*

The Heterodyne Sweep Generator

Circuit detail of the heterodyne sweep generator is shown in Figure 13.34. The operation is described as follows:

The *XR205* sawtooth generator N_I drives a voltage-controlled oscillator N_2 operating at a fixed centre frequency of 1 MHz. This is a very stable IC package type *XR*2209 which can operate at 1 MHz with its frequency set by external *R* and *C* components. Its output at Pin 8 is a triangular waveform and this is shaped to a sine wave by *LP* filter L_1, C_{10}, L_2 and C_{11}. The sweep-frequency span is controlled by the amplitude of the sawtooth wave and this is set by the potentiometer R8.

The 1 MHz sweep output is mixed with an external variable signal source (such as a standard signal generator) in a double balanced mixer N_3. This balances out the two input signals and delivers two frequencies which are the sum and difference of the input signal frequencies. The well-known MC1496 is used for this function and provides a high output level of mixed signals up to around 20 MHz with output falling off as 25 MHz is approached. Its low-frequency performance is limited to around 100 kHz by the primary inductance of coupling transformer T_I, wound on a small ferrite toroidal core. Output level is set by the potentiometer *R*24 coupled via emitter follower stage V_1 to provide low output impedance. For satisfactory operation, the signal level from the external signal source needs to be around 0.1 to 0.5 VPP.

To set up for a given output frequency, it is only necessary to set the external signal generator to a frequency 1 MHz removed from the required frequency. No tuning is required in the sweep generator itself. Of course, there is always a second image frequency component at the output, but as the filter or IF channel being tested is itself a selective band-limiting device, the image component is rejected from reaching the detector circuit.

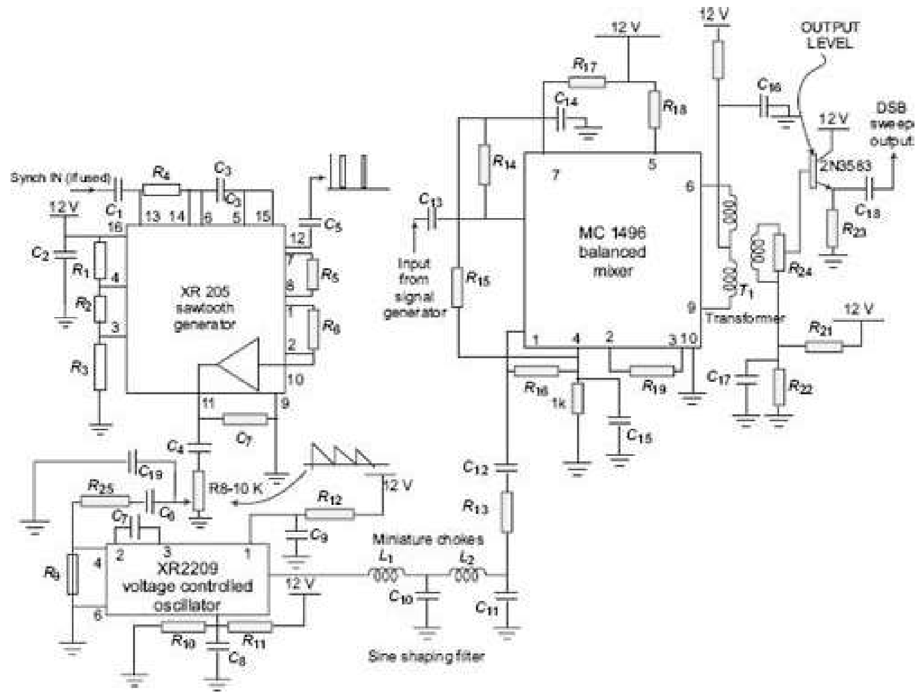

Figure 13.34 *Heterodyne sweep generator (100 kHz to 25 MHz) showing sawtooth generator, voltage controlled oscillator and mixer circuits*

From an operational point of view, the precise centre frequency of the fixed internal sweep oscillator is not important. However, by setting it right at 1 MHz, the frequency required from the external oscillator becomes obvious without putting pencil to paper or referring to the calculator. The precise frequency of the oscillator can be set to 1 MHz by trimming the value of C7. The *XR2209* is a very stable oscillator provided its supply voltage is held constant. Hence, the 12 V supply to the sweep generator must be regulated.

The MC1496 (N_3) used was the TO5 package and the pin numbers shown are for that package. The pin numbers for the DIL package would be different. Packages N_1 and N_2 are both DIL types.

13.16 WAVE ANALYSER

It is well known that any periodic waveform can be represented as a sum of a dc component and a series of sinusoidal harmonics. Analysis of a waveform consists of determination of the values of amplitudes, frequency and sometimes phase angle of the harmonic components. Graphical and mathematical methods may be used for the purpose but methods are quite laborised. The analysis of a complex waveform can be done by electrical means using a bandpass filter network to single out the various harmonic components. Networks of these types pass a narrow band of frequency and provide a high degree of assumptions to all other frequencies.

A wave analyser, in fact, is an instrument designed to measure relative amplitude of single frequency components in a complex waveform. Basically, the instrument acts as a frequency selective voltmeter which is turned to the frequency of one signal while rejecting all other signal components. The desired frequency is selected by a frequency calibrated dial to the point of maximum amplitude. The amplitude is indicated either by a suitable voltmeter or a CRO.

There are two types of wave analyser, depending upon frequency ranges used: (i) frequency selective wave analyser and (ii) heterodyne wave analyser.

13.16.1 Frequency Selective Wave Analyser

This wave analyser is employed in audio-frequency-range (20 Hz to 20 kHz) measurement. It consists of a narrow band pass filter which can be tuned to the frequency of interest. The block diagram of this analyser is shown in Figure 13.35. The waveform to be analysed in terms of its separate frequency components is applied to an input attenuator that is set by the meter range switch on the front panel. A driver amplifier feeds the attenuated waveform to a high-*Q* active filter. The filter consists of a cascaded arrangement of *RC* resonant sections and filter amplifiers. The passband of the whole filter section is covered in decade steps over the entire audio range by switch capacitors in the *RC* sections. Close-tolerance polystyrene capacitors are generally used for selecting the frequency ranges. Precision potentiometers are used to tune the filter to any desired frequency within the selection passband. The final amplifier stage supplies the selected signal to the meter circuit and to an unturned buffer amplifier. The buffer amplifier can be used to drive a recorder or an electronic counter. The meter is driven by an average type detector and usually has several voltage ranges as well as a decibel scale. The bandwidth is very narrow, typically about 1% of the selected frequency. Figure 13.36 shows a typical attenuation curve of a wave analyser.

13.16.2 Heterodyne Wave Analyser

This wave analyser is used to measure the frequency in megahertz range. The block diagram of this wave analyser is shown in Figure 13.37. The signal as input is fed through an attenuator and amplifier before being mixed with a local oscillator signal. The frequency of this oscillator is adjusted to give a fixed frequency output which is in the pass band of the amplifier. In the next stage, this signal is mixed with a second crystal oscillator, whose frequency is such that the output from the mixer is centreed on zero frequency. The subsequent active filter has a controllable bandwidth, and passes the selected component of the frequency to the indicating meter. Good frequency stability in a wave analyser is achieved by using frequency synthesisers, which have high accuracy and resolution, or by automatic frequency control. In an automatic frequency control system, the local oscillator locks to the signal, and so eliminates the drift between them.

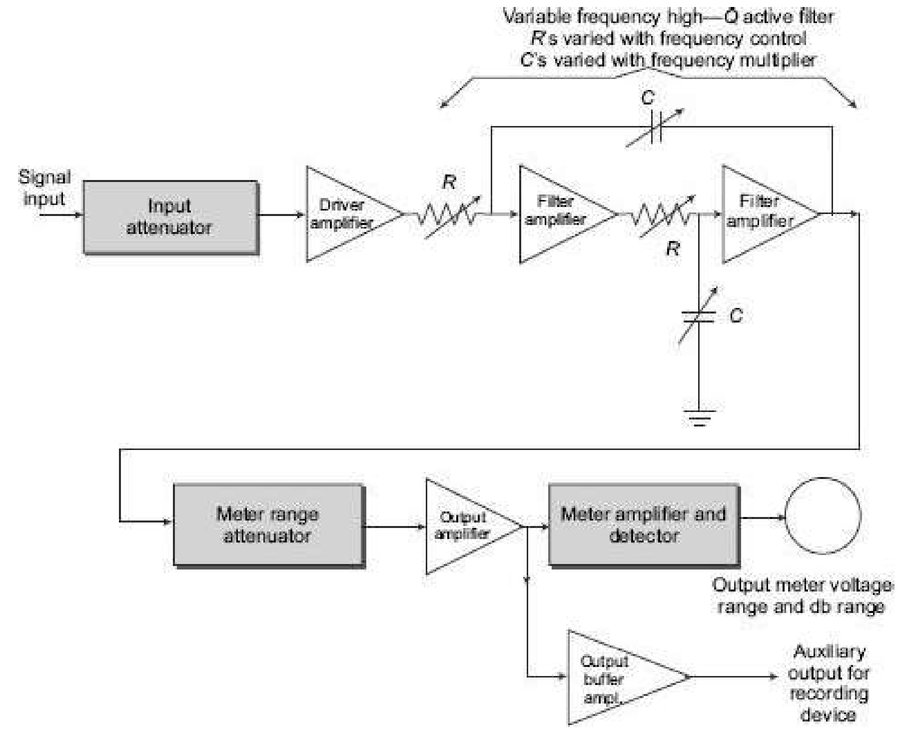

Figure 13.35 *Block diagram of a frequency selective wave analyser*

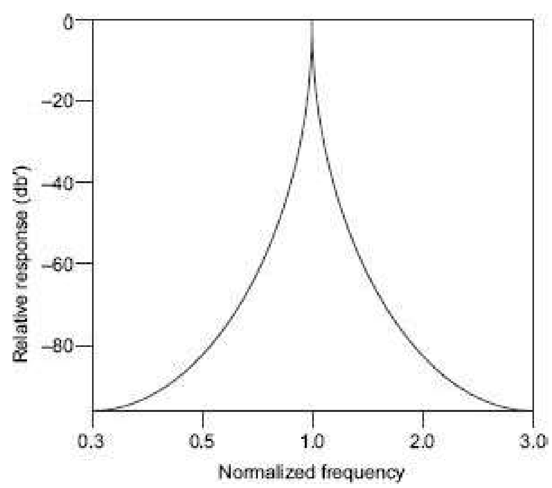

Figure 13.36 *Attenuation of a wave analyser*

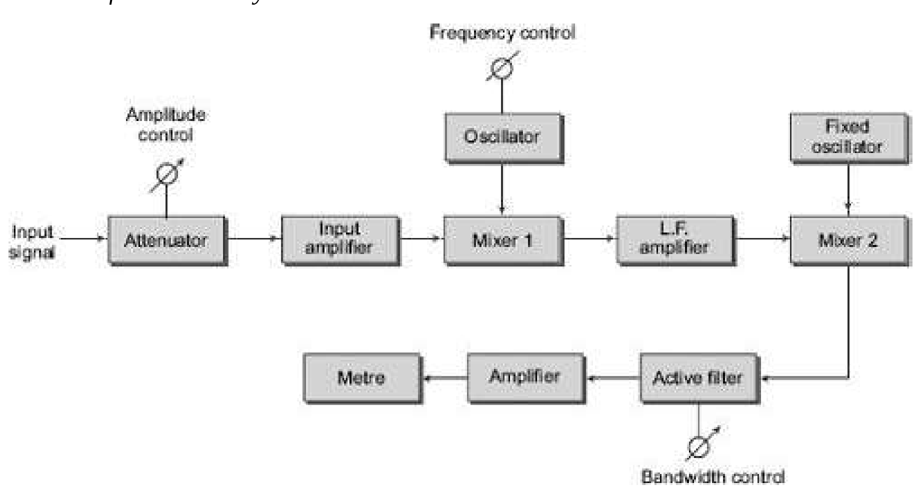

Figure 13.37 *Block diagram of a heterodyne wave analyser*

13.16.3 Applications of Wave Analysers

Wave analysers have very important applications in the field of i) electrical measurements, ii) sound measurements, and iii) vibration measurements.

Wave analysers are used industrially to detect and reduce the sound and vibration generated by rotating electrical machines and equipment. A good spectrum analysis with a wave analyser shows various discrete frequencies and resonances that can be related to the motion of machines.

13.17 HARMONIC DISTORTION ANALYSERS

Generally, the output waveform of an electronic device, such as an amplifier, should become an exact replica of the input waveform. However, in most of the cases that does not happen due to the introduction of various types of distortions. Distortions may be a result of the inherent non-linear characteristics of components used in the electronic circuit. Non-linear behaviour of circuit elements introduces harmonics in the output waveform and the resultant distortion is often termed Harmonic Distortion (HD).

Types of Distortion

The various types of distortions which occur are explained below.

1. Frequency Distortion

This distortion occurs due to the amplification factor of the amplifier is different for different frequencies.

2. Phase distortion

This distortion occurs due to the presence of energy-storage elements in the system, which cause the output signal to be displaced in phase with the input signal. If signals of all frequencies are displaced by the same amount, the phase shift distortion would not be observed. However, in actual practice, signals at different frequencies are shifted in phase by different angles and therefore, the phase-shift distortion becomes noticeable.

3. Amplitude Distortion

Harmonic distortion occurs due to the fact that the amplifier generates harmonics of the fundamental of the input signal. Harmonics always give rise to amplitude distortion, for example, when an amplifier is overdriven and clips the input signals.

4. Inter-modulation Distortion

This type of distortion occurs as a consequence of interaction or heterodyning of two frequencies, giving an output which is the sum or difference of the two original frequencies.

5. Cross-over Distortion

This type of distortion occurs in push-pull amplifier due to incorrect bias levels.

6. Total Harmonic Distortion

A non-linear system produces harmonics of an input sine wave, the harmonics consists of a sine wave with frequencies which are multiples of the fundamental of the input signal. The Total Harmonic Distortion (THD) is measured in terms of the harmonic contents of the wave, as given by

$$\mathrm{THD} = \frac{\left[\sum (\text{Harrmonics})^2\right]^{\frac{1}{2}}}{\text{Fundamental}} \times 100\%$$

In a measurement system, noise is read in addition to harmonics, and the total waveform, consisting of harmonics, noise and fundamental, is measured instead of the fundamental alone. Therefore, the measured value of the total harmonic distortion ($\mathrm{THD_M}$) is given by

$$\mathrm{THD}_M = \frac{\left[\sum \{(\text{Harmonics})^2 + (\text{Noise})^2\}\right]^{\frac{1}{2}}}{\left[\sum \{(\text{Fundamental})^2 + (\text{Harmonics})^2 + (\text{Noise})^2\}\right]^{\frac{1}{2}}}$$

Figure 13.38 shows the block diagram of a harmonic distortion analyser which is used to measure THD. The signal source has very low distortion and this can be checked by reading its output distortion by connecting directly into the analyser. The signal from the source is fed into the amplifier under test. This generates harmonics and the original fundamental frequency. The fundamental frequency is removed by a notch filter. In the manual system, as shown in Figure 13.38 (a), the switch *S* is first placed in the position 1 and the total content of fundamental and harmonics (E_T) is measured. Then the switch is moved to the position 2 to measure just the harmonics E_H. the value of THD is then found using following equation:

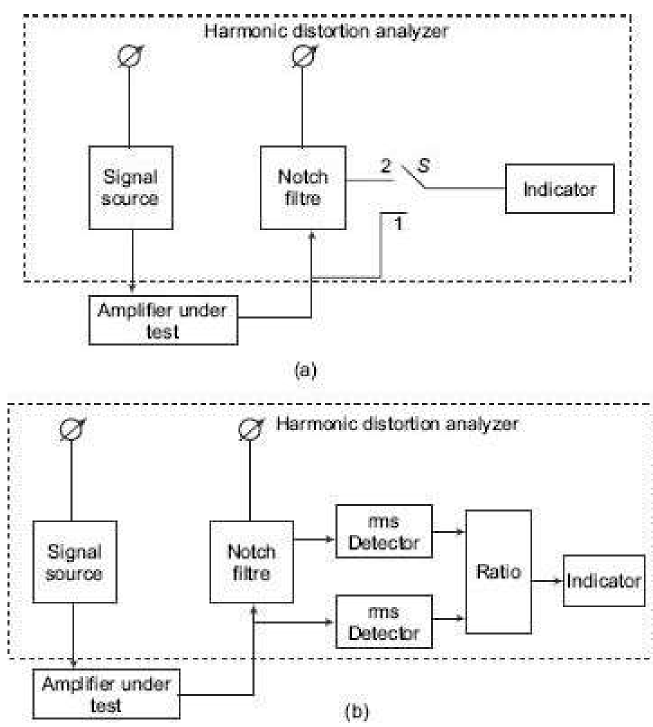

Figure 13.38 *Simplified block diagrams of fundamental suppression harmonic distortion analysers: (a) Manual reading (b) Ratio reading*

$$\mathrm{THD} = \frac{E_H}{E_T} \times 100\%$$

The meter can be calibrated by putting the switch in the position 1 and adjusting the reading for full scale deflection. With the switch position 2, the meter reading is now proportional to THD. Figure 13.28(b) shows an alternative arrangement, where the value of E_T and E_H are read simultaneously and their ratio calculated and displayed as THD on the indicator. For good accuracy, the notch filter must have excellent rejection and high pass characteristics. It should attenuate the fundamental by 100 db or more and the harmonics by less than 1 db. The filter also needs to be tuned accurately to the fundamental of the signal source. This is difficult to achieve manually and most distortion analysers do this automatically. A common form of notch filter is a Wien bridge. This balances at one frequency only and at this frequency, the output voltage at the bridge null detector is minimum.

13.18 SPECTRUM ANALYSER

A spectrum analyser is a wide band, very sensitive receiver. It works on the principle of "superheterodyne receiver" to convert higher frequencies (normally ranging up to several 10s of GHz) to measurable quantities. The received frequency spectrum is slowly swept through a range of pre-selected frequencies, converting the selected frequency to a measurable dc level (usually logarithmic scale), and displaying the same on a CRT. The CRT displays received signal strength (y-axis) against frequency (x-axis).

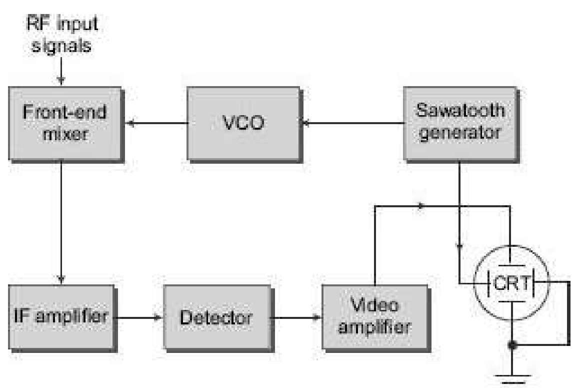

Figure 13.39 *Simplified block diagram of a super-heterodyne receiver*

As seen from Figure 13.39, it consists of the following parts:

1. Front-end mixer
2. Voltage controlled oscillator
3. Sawtooth generator
4. IF amplifier
5. Detector
6. Video amplifier
7. Cathode Ray Tube (CRT)

The front-end mixer is where the RF input is combined with the local oscillator (VCO) frequency to give IF (Intermediate Frequency) output. The IF frequencies are then fed to an IF amplifier, then to a detector. The output of the detector is fed to the video amplifier. The output from the video amplifier is given to CRT (vertical axis), and the output of the sawtooth generator is given to the horizontal axis of the CRT. Thus, we see the signal amplitude against the time sweep (which in turn represents the frequency).

Normally, the frequency conversion takes place in multiple stages, and band-pass filters are used to shape the signals. Also, precision amplifiers and detectors are used to amplify and detect the signals.

Obviously, signals that are weaker than the background noise could not be measured by a spectrum analyser. For this reason, the noise floor of a spectrum analyser in combination with RBW is a vital parameter to be considered when choosing a spectrum analyser. The received signal strength is normally measured in decibels (dbm). (Note that 0 dBm corresponds to 1 mWatt of power on a logarithmic scale). The primary reasons for measuring the power (in dBm) rather than voltage in spectrum analysers are the low received signal strength, and the frequency range of measurement. Spectrum analysers are capable of measuring the frequency response of a device at power levels as low as −120 dBm. These power levels are encountered frequently in microwave receivers, and spectrum analysers are capable of measuring the device characteristics at those power levels.

13.18.1 Spectrum Analyser Vs Oscilloscope

1. A spectrum analyser displays received signal strength (*y*-axis) against frequency (*x*-axis). An oscilloscope displays received signal strength (*y*-axis) against time (*x*-axis).
2. A Spectrum analyser is useful for analysing the amplitude response of a device against frequency. The amplitude is normally measured in dBm in spectrum analysers, whereas the same is measured in volts when using oscilloscopes.
3. Normally, an oscilloscope cannot measure very low voltage levels (say, −100 dBm) and are intended for low-frequency, high-amplitude measurements. A spectrum analyser can easily measure very low amplitudes (as low as −120 dBm), and high frequencies (as high as 150 GHz).
4. The spectrum analyser measurements are in frequency domain, whereas the oscilloscope measurements are in time domain.
5. Also, a spectrum analyser uses complex circuitry compared with an oscilloscope. As a result of this, the cost of a spectrum analyser is usually quite high.

A *signal* is usually defined by a time-varying function carrying some sort of information. Such a function most often represents a time-changing electric or magnetic field, whose propagation can be in free space or in dielectric materials constrained by conductors (waveguides, coaxial cables, etc.). A signal is said to be periodic if it repeats itself exactly after a given time T called the period. The inverse of the period T, measured in seconds, is the frequency f measured in hertz (Hz).

A periodic signal can always be represented in terms of a sum of several (possibly infinite) sinusoidal signals, with suitable amplitude and phase, and having frequencies that are integer multiples of the signal frequency. Assuming an electric signal, the square of the amplitudes of such sinusoidal signals represents the power in each sinusoid, and is said to be the power spectrum of the signal. These concepts can be generalised to an aperiodic signal; in this case, its representation (spectrum) will include a continuous interval of frequencies, instead of a discrete distribution of integer multiples of the fundamental frequency.

The representation of a signal in terms of its sinusoidal components is called *Fourier analysis.* The (complex) function describing the distribution of amplitudes and phases of the sinusoids composing a signal is called its *Fourier Transform* (FT). The Fourier analysis can be readily generalised to functions of two or more variables; for instance, the FT of a function of two (spatial) variables is the starting point of many techniques of image processing. A time-dependent electrical signal can be analysed directly as a function of time with an *oscilloscope* which is said to operate in the *time domain.* The time evolution of the signal is then displayed and evaluated on the vertical and horizontal scales of the screen.

The *spectrum analyser* is said to operate in the *frequency domain* because it allows one to measure the harmonic content of an electric signal, that is, the power of each of its spectral components. In this case, the vertical and horizontal scales read powers and frequencies. The two domains are mathematically well defined and, through the FT algorithm, it is not too difficult to switch from one response to the other.

Their graphical, easily perceivable representation is shown in Figure 13.40, where the two responses are shown lying on orthogonal planes. It is trivial to say that the easiest way to make a Fourier analysis of a time-dependent signal is to have it displayed on a spectrum analyser. Many physical processes produce (electric) signals whose nature is not deterministic, but rather stochastic, or random (noise). Such signals can also be analysed in terms of FT, although in a statistical sense only. A time signal is said to be band-limited if its FT is nonzero only in a finite interval of frequencies, say $(F_{max} - F_{min})$ = B. Usually, this is the case and an average frequency F_0 can be defined. Although the definition is somewhat arbitrary, a (band-limited) signal is referred to as RF (radio frequency) if F_0 is in the range 100 kHz to 1 GHz and as a microwave signal in the range 1 to 1000 GHz. The distinction is not fundamental theoretically, but it has very strong practical implications in instrumentation and spectral measuring techniques. A band-limited signal can be described further as narrow band, if $B/F0 <= 1$, or wide band otherwise.

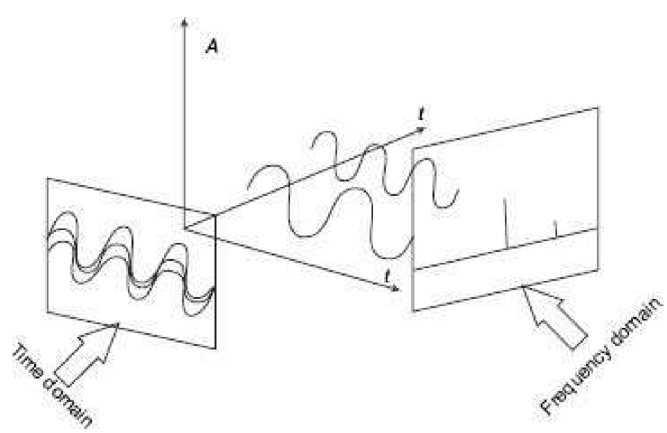

Figure 13.40 *How the same signal can be displayed*

The first step in performing a spectral analysis of a narrow-band signal is generally the so-called heterodyne down-conversion: it consists in the mixing (beating) of the signal with a pure sinusoidal signal of frequency F_L, called Local Oscillator *(LO).* In principle, mixing two signals of frequency F_0 and F_L in any nonlinear device will result in a signal output containing the original frequencies as well as the difference ($F_0 - F_L$) and the sum ($F_0 + F_L$) frequencies, and all their harmonic (multiple) frequencies. In the practical case, a purely quadratic mixer is used, with an *LO* frequency $F_L < F_0$; the output will include the frequencies ($F_0 - FL$), $2FL$, $2F_0$, and ($F_0 + F_L$), and the first term (called the intermediate frequency or IF) will be easily separated from the others, which have a much higher frequency. The bandwidth of the IF signal will be the same as the original bandwidth *B*; however, to preserve the original information fully in the IF signal, stringent limits must be imposed on the *LO* signal, because any deviation from a pure sinusoidal law will show up in the IF signal as added phase and amplitude noise, corrupting the original spectral content. The process of down converting a (band-limited) signal is generally necessary to perform spectral analysis in the very-high-frequency (microwave) region, to convert the signal to a frequency range more easily handled technically.When the heterodyne process is applied to a wideband signal (or whenever $F_L > F_{\min}$), "negative" frequencies will appear in the IF signal. This process is called *double sideband* mixing, because a given IF bandwidth *B* (i.e., $(FL + B/2)$ will include two separate bands of the original signal, centreed at F_L + IF ("upper" sideband) and F_L − IF ("lower" sideband). This form of mixing is obviously undesirable in spectrum analysis, and input filters are generally necessary to split a wide-band signal in several narrow-band signals before down conversion. Alternatively, special mixers can be used that can deliver the upper and lower sidebands to separate IF channels. A band-limited signal in the frequency interval $(F_{\max} - F_{\min}) = B$ is said to be converted to baseband when the *LO* is placed at $F_L = F_{\min}$, so that the band is converted to the interval $(B - 0)$. No further lowering of frequency is then possible, unless the signal is split into separate frequency bands by means of filters. After down conversion, the techniques employed to perform power-spectrum analysis vary considerably depending on the frequencies involved. At lower frequencies, it is possible to employ analog-to-digital converters (ADC) to get a discrete numerical representation of the analog signal, and the spectral analysis is then performed numerically, either by direct computation of the FT (generally via the fast Fourier transform, FFT, algorithm) or by computation of the signal autocorrelation function, which is directly related to the square modulus of the FT via the Wiener-Khinchin theorem. Considering that the ADC must sample the signal at least at the Nyquist rate (i.e. at twice the highest frequency present) and with adequate digital resolution, this process is feasible and practical only for frequencies (bandwidths) less than a few megahertz. Also, the possibility of a real-time analysis with high spectral resolution may be limited by the availability of very fast digital electronics and special-purpose computers. The digital approach is the only one that can provide extremely high spectral resolution, up to several hundred thousand channels. For high frequencies, several analog techniques are employed.

13.18.2 A Practical Approach to Spectrum Analysis

Spectrum analysis is normally done in order to verify the harmonic content of oscillators, transmitters, frequency multipliers, etc. or the spurious components of amplifiers and mixers. Other specialised applications are possible, such as the monitoring of Radio Frequency Interference (RFI), Electromagnetic Interference (EMI), and Electromagnetic Compatibility (EMC). These applications, as a rule, require an antenna connection and a low-noise, external amplifier. Which are then the specifications to look for in a good spectrum analyser? We would suggest the following:

1. It should display selectable, very wide bands of the EM radio spectrum with power and frequency readable with good accuracy.
2. Its selectivity should range, in discrete steps, from a few hertz to megahertz so that sidebands of a selected signal can be spotted and shown with the necessary details.
3. It should possess a very wide dynamic range, so that signals differing in amplitude six to eight orders of magnitude can be observed at the same time on the display.
4. Its sensitivity must be compatible with the measurements to be taken. As already mentioned, specialised applications may require external wide-band, low-noise amplifiers and an antenna connection.
5. Stability and reliability are major requests but they are met most of the time.

Occasionally, a battery-operated option for portable field applications may be necessary. A block diagram of a commercial spectrum analyser is shown in Figure 13.41.

Referring to Figure 13.41, we can say that we are confronted with a radio-receiver-like superhet with a wide-band input circuit. The horizontal scale of the instrument is driven by a ramp generator which is also applied to the voltage-controlled *LO* [2].

A problem arises when dealing with a broadband mixing configuration like the one shown above, namely, avoiding receiving the image band.

The problem is successfully tackled here by upconverting the input band to a high-valued IF. An easily designed input low-pass filter, not shown in the block diagram for simplicity, will now provide the necessary rejection of the unwanted image band.

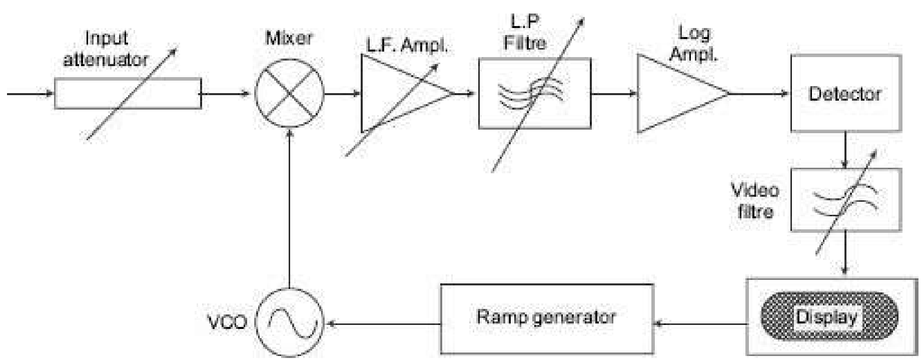

Figure 13.41 *Block diagram of a commercial spectrum analyser*

Nowadays, with the introduction of YIG bandpass filter preselectors, tunable over very wide input bands, up conversion is not always necessary. Traces of unwanted signals may, however, show up on the display although at very low level (less than −80 dBc) on good analysers.

A block diagram of a commercial spectrum analyser exploiting both the mentioned principles is shown in Figure 13.41. This instrument includes a very important feature which greatly improves its performance: the *LO* frequency is no longer coming from a free-running source but rather from a synthesised unit referenced to a very stable quartz oscillator. The improved quality of the *LO*, both in terms of its own noise and frequency stability, optimises several specifications of the instrument, such as frequency-determining accuracy, finer resolution on display, and reduced noise in general.

Further, a stable *LO* generates stable harmonics which can then be used to widen the input-selected bands up to the millimetre region. As already stated, this option requires external devices, e.g. a mixer. The power reference on the screen is the top horizontal line of the reticle. Due to the very wide dynamic range foreseen, the use of a log scale (e.g., 10 dB/square) seems appropriate. Conventionally, 1 mW is taken as the zero reference level: accordingly, dBm is used throughout. The noise power level present on the display without an input signal connected (noise floor) is due to the input random noise multiplied by the IF amplifier gain. Such a noise is always present and varies with input frequency, IF selectivity, and analyser sensitivity (in terms of noise figure 13.13.). The "on-display dynamic range" of the analyser is the difference between the maximum compression-free level of the input signal and the noise floor. As a guideline, the dynamic range of a good instrument could be of the order of 70 to 90 dB.

An input attenuator, always available on the front panel, allows one to apply more power to the analyser while avoiding saturation and nonlinear readings. The only drawback is the obvious sensitivity loss. One should not expect a spectrum analyser to give absolute power-level readings to be better than a couple of dB.

For the accurate measurement of power levels, the suggestion is to use a power meter. An erratic signal pattern on display and a fancy level indication may be caused by the wrong setting of the "scan time" knob. It must be realised that high-resolution observation of a wide input band requires proper scanning time. An incorrect parameter setting yields wrong readings but usually an optical alarm is automatically switched on to warn the operator.

13.18.3 Spectrum Analyser Applications

1. Device Frequency Response Measurements

You can use spectrum analysers for measuring the amplitude response (typically measured in dbm) against frequency of the device. The device may be anything from a broadband amplifier to a narrowband filter.

2. Microware Tower Monitoring

You can measure the transmitted power and received power of a microware tower. Typically, you use a directional coupler to tap the power without interrupting the communications. In this way, you can verify that the frequency and signal strength of your transmitter are according to the specified values.

3. Interference Measurements

Any large RF installations normally require site survey. A spectrum analyser can be used to verify and identify interferences. Any such interfering signals need to be minimised before going ahead with the site work. Interference can be created by a number of different sources, such as telecom microwave towers, TV stations, airport guidance systems, etc.

Other measurements that could be made using a spectrum analyser include the following:

- Return-loss measurement
- Satellite antenna alignment
- Spurious signals measurement
- Harmonic measurements
- Inter-modulation measurements

Given below are some important features available with few portable spectrum analyser of 9 kHz to 26.5 GHz:

- Colour display
- Continuous 30 Hz to 26.5 GHz sweep
- Fast digital resolution bandwidths of 1, 3, 10, 30 and 100 Hz
- Adjacent channel power, channel power, carrier power, occupied bandwidth percentage and time-gated measurements standard
- Precision timebase and 1 Hz counter resolution
- Measurement personalities for digital radio and phase noise measurements
- Easily transfer screen image or trace data to PC

Note: The above specifications are given as an example only, and may not accurately represent the actual equipment specifications.

EXERCISE

Objective-type Questions

1. Which one of the following oscillators is used for generation of high frequencies?
   (a) *RC* phase shift
   (b) Wien bridge
   (c) *LC* oscillator
   (d) Blocking oscillator
2. A triangular wave can be generated by
   (a) integrating a square wave
   (b) differentiating a square wave
   (c) integrating a sine wave
   (d) differentiating a sine wave
3. Harmonic distortion is due to
   (a) change in the behaviour of circuit elements due to change in temperature
   (b) change in the behaviour of circuit elements due to change in environment
   (c) linear behaviour of circuit elements
   (d) nonlinear behaviour of circuit elements
4. A spectrum analyser is a combination of
   (a) narrow band super-heterodyne receiver and CRO
   (b) signal generator and CRO
   (c) oscillator and wave analyser

(d) VTVM and CRO

5. A spectrum analyser is used across the frequency spectrum of a given signal to study the
   (a) current distribution
   (b) voltage distribution
   (c) energy distribution
   (d) power distribution

Answers

1. (b) 2. (a) 3. (d) 4. (a) 5. (d)

Short-answer Questions

1. What is the initial condition for an oscillator to start?
2. What are the Barkhausen conditions of oscillations?
3. Why are *LC* resonant circuits impractical at audio frequencies?
4. Why is a crystal oscillator preferred in communication transmitters and receivers?
5. What is a function generator?
6. What is the basic difference between a square-wave generator and pulse generator?
7. What is a Schmitt trigger circuit? Discuss the applications of a Schmitt trigger circuit.
8. What is a VCO? Explain its working principle.

Long-answer Questions

1. Classify oscillators on the basis of design principle. How can an amplifier be converted into an oscillator? What is the role of resonance in an oscillator circuit?
2. What is an oscillator? How does it differ from an amplifier? What are the major parts of an oscillator circuit?
3. Draw the circuit diagram of a Hartley oscillator and explain its operation.
4. Draw the circuit diagram of a Colpitts oscillator and explain its operation.
5. Enumerate the advantages of *RC* oscillators. Explain the working of an *RC* phase shift oscillator.
6. Draw and explain the circuit of the Wien bridge oscillator. Derive the expression for frequency of oscillation for such an oscillator. Will oscillations take place if the bridge is balanced?
7. What are the requirements of pulse? Draw a circuit diagram of a generator which produces such pulses.
8. Explain the working of a function generator producing sine, square and triangular waveforms. Draw its block diagram.
9. Draw the circuit diagram of a stable multivibrator. How does it generate square wave?
10. Describe with a block diagram a sweep-frequency generator and its applications.
11. Discuss the working of a wave analyser.
12. With the help of a block diagram, explain the working of a harmonic distortion analyser.
13. What is a wave analyser? Explain the working principle of a heterodyne wave analyser.
14. Distinguish the principles of the working of a spectrum analyser and a wave analyser. Draw the block diagram of a spectrum analyser. Indicate the common applications of a spectrum analyser.