UNIT V FEEDBACK AMPLIFIERS AND OSCILLATORS

By
Mr. R. Suresh, AP/RMDEEE
Ms. S. Karkuzhali, AP/RMDEEE
Feedback Amplifiers

1 - Desensitize The Gain

2 - Reduce Nonlinear Distortions

3 - Reduce The Effect of Noise

4 – Control The Input And Output Impedances

5 – Extend The Bandwidth Of The Amplifier
Basic structure of a feedback amplifier. To make it general, the figure shows signal flow as opposed to voltages or currents (i.e., signals can be either current or voltage).

The open-loop amplifier has gain $A \rightarrow x_o = A x_i$

Output is fed back through a feedback network which produces a sample ($x_f$) of the output ($x_o$) $\rightarrow x_f = \beta x_o$

Where $\beta$ is called the feedback factor

The input to the amplifier is $x_i = x_s - x_f$ (the subtraction makes feedback negative)

Implicit to the above analysis is that neither the feedback block nor the load affect the amplifier’s gain ($A$). This not generally true and so we will later see how to deal with it.

The overall gain (closed-loop gain) can be solved to be:

$$A_f \equiv \frac{x_o}{x_s} = \frac{A}{1 + A\beta}$$

$A_\beta$ is called the loop gain $1 + A_\beta$ is called the “amount of feedback”
Finding Loop Gain

Generally, we can find the loop gain with the following steps:

– Break the feedback loop anywhere (at the output in the ex. below)
– Zero out the input signal \( x_s \)
– Apply a test signal to the input of the feedback circuit
– Solve for the resulting signal \( x_o \) at the output
  
  If \( x_o \) is a voltage signal, \( x_{tst} \) is a voltage and measure the open-circuit voltage
  
  If \( x_o \) is a current signal, \( x_{tst} \) is a current and measure the short-circuit current

– The negative sign comes from the fact that we are apply negative feedback

\[
\begin{align*}
  x_s &= 0 \\
  x_i &= 0 - x_f \\
  x_o &= Ax_i = -Ax_f = -\beta A x_{tst} \\
  \text{loop gain} &= -\frac{x_o}{x_{tst}} = \beta A 
\end{align*}
\]
Negative Feedback Properties

Negative feedback takes a sample of the output signal and applies it to the input to get several desirable properties. In amplifiers, negative feedback can be applied to get the following properties:

– Desensitized gain – gain less sensitive to circuit component variations

– Reduce nonlinear distortion – output proportional to input (constant gain independent of signal level)

– Reduce effect of noise

– Control input and output impedances – by applying appropriate feedback topologies

– Extend bandwidth of amplifier

These properties can be achieved by trading off gain.
Gain Desensitivity

Feedback can be used to desensitize the closed-loop gain to variations in the basic amplifier. Let’s see how.

Assume beta is constant. Taking differentials of the closed-loop gain equation gives…

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

Divide by \( A_f \)

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

This result shows the effects of variations in \( A \) on \( A_f \) is mitigated by the feedback amount. \( 1+Abeta \) is also called the desensitivity amount.

We will see through examples that feedback also affects the input and resistance of the amplifier (increases \( R_i \) and decreases \( R_o \) by \( 1+Abeta \) factor)
Bandwidth Extension

Mentioned several times in the past that we can trade gain for bandwidth. Consider an amplifier with a high-frequency response characterized by a single pole and the expression:

Apply negative feedback beta and the resulting closed-loop gain is:

\[ A(s) = \frac{A_M}{1 + s/\omega_H} \]

\[ A_f(s) = \frac{A(s)}{1 + \beta A(s)} = \frac{A_M/(1 + A_M \beta)}{1 + s/\omega_H(1 + A_M \beta)} \]

Notice that the midband gain reduces by \((1+A_M\beta)\) while the 3-dB roll-off frequency increases by \((1+A_M\beta)\)
Basic Feedback Topologies

Depending on the input signal (voltage or current) to be amplified and form of the output (voltage or current), amplifiers can be classified into four categories. Depending on the amplifier category, one of four types of feedback structures should be used (series-shunt, series-series, shunt-shunt, or shunt-series) Voltage amplifier – voltage-controlled voltage source
Requires high input impedance, low output impedance
Use series-shunt feedback (voltage-voltage feedback)

Current amplifier – current-controlled current source
Use shunt-series feedback (current-current feedback)

Transconductance amplifier – voltage-controlled current source
Use series-series feedback (current-voltage feedback)

Transimpedance amplifier – current-controlled voltage source
Use shunt-shunt feedback (voltage-current feedback)
Examples of the Four Types of Amplifiers

- Shown above are simple examples of the four types of amplifiers. Often, these amplifiers alone do not have good performance (high output impedance, low gain, etc.) and are augmented by additional amplifier stages (see below) or different configurations (e.g., cascoding).
Series-Shunt Feedback Amplifier (Voltage-Voltage Feedback)

Samples the output voltage and returns a feedback voltage signal

Ideal feedback network has infinite input impedance and zero output resistance

Find the closed-loop gain and input resistance

The output resistance can be found by applying a test voltage to the output

So, increases input resistance and reduces output resistance \( \rightarrow \) makes amplifier closer to ideal VCVS

\[
V_f = \beta V_o
\]

\[
V_i = V_s - V_f
\]

\[
V_o = A(V_s - \beta V_o)
\]

\[
A_f \equiv \frac{V_o}{V_s} = \frac{A}{1 + \beta A}
\]

\[
R_{if} = \frac{V_s}{I_i} = \frac{V_s}{V_i/R_i} = R_i \frac{V_s}{V_i} = R_i \frac{V_i + \beta AV_i}{V_i} = R_i(1 + A\beta)
\]

\[
R_{of} = \frac{R_o}{1 + \beta A}
\]
The Series-Shunt Feedback Amplifier

The Ideal Situation

The series-shunt feedback amplifier:

(a) ideal structure;
(b) equivalent circuit.

\[ A_f = \frac{V_o}{V_s} = \frac{A}{1 + A \cdot \beta} \]

\[ R_{if} = \frac{V_s}{I_i} = \frac{V_s}{V_i} = \frac{V_s}{R_i} \cdot \frac{V_i + \beta \cdot A \cdot V_i}{V_i} = R_i \cdot \frac{V_i + \beta \cdot A \cdot V_i}{V_i} \]

\[ R_{if} = R_i \cdot (1 + A \cdot \beta) \]

\[ Z_{if}(s) = Z_i(s) \cdot (1 + A(s) \cdot \beta(s)) \]
Series-Series Feedback Amplifier (Current-Voltage Feedback)

For a transconductance amplifier (voltage input, current output), we must apply the appropriate feedback circuit.

Sense the output current and feedback a voltage signal. So, the feedback current is a transimpedance block that converts the current signal into a voltage.

To solve for the loop gain:

Break the feedback, short out the break in the current sense and applying a test current.

To solve for $R_{if}$ and $R_{of}$:

Apply a test voltage $V_{tst}$ across $O$ and $O'$.

$$A_f = \frac{I_o}{V_s} = \frac{A}{1 + A\beta}$$  
Loop Gain $= A\beta = -\frac{I_{out}}{I_{tst}} = G_m R_f$

$$R_{if} = \frac{V_{s}}{I_i} = \frac{V_i + V_f}{I_i} = \frac{R_i I_i + \beta I_o}{I_i} = R_i \left(1 + A\beta\right)$$

$$R_{of} = \frac{V_{tst}}{I_{tst}} = \left(\frac{I_{tst} - AV_i}{I_{tst}}\right) R_o = \left(\frac{I_{tst} + A\beta I_{tst}}{I_{tst}}\right) R_o = (1 + A\beta) R_o$$
Shunt-Shunt Feedback Amplifier
(Voltage-Current Feedback)

- When voltage-current FB is applied to a transimpedance amplifier, output voltage is sensed and current is subtracted from the input
  - The gain stage has some resistance
  - The feedback stage is a transconductor
  - Input and output resistances \((R_{if} \text{ and } R_{of})\) follow the same form as before based on values for \(A\) and beta

\[
A = \frac{V_o}{I_i}
\]

\[
I_s = I_i + I_f = \frac{V_o}{A} + \beta V_o
\]

\[
A_f \equiv \frac{V_o}{I_s} = \frac{A}{1 + A \beta}
\]

\[
R_{if} = R_i (1 + A \beta)
\]

\[
R_{of} = \frac{R_o}{(1 + A \beta)}
\]
Shunt-Series Feedback Amplifier (Current-Current Feedback)

- A current-current FB circuit is used for current amplifiers
  - For the b circuit – input resistance should be low and output resistance be high
- A circuit example is shown
  - $R_S$ and $R_F$ constitute the FB circuit
    - $R_S$ should be small and $R_F$ large
    - The same steps can be taken to solve for $A$, $\alpha$, $A_f$, $R_{if}$, and $R_{of}$
      - Remember that both $A$ and $b$ circuits are current controlled current sources
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Voltage series</th>
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<td>Decreases</td>
<td>Decreases</td>
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<td>Decreases</td>
<td>Decreases</td>
<td>Decreases</td>
</tr>
</tbody>
</table>
The General Feedback Structure

Exercise

\[ A_f := 10 \quad A := 10^4 \]

a) \[ \beta = \frac{R_1}{R_1 + R_2} \]

b) \[ A_f = \frac{A}{1 + A \cdot \beta} \]

\[ \beta := 1 \]

given

\[ A_f = \frac{A}{1 + A \cdot \beta} \]

\[ \beta := \text{Find}(\beta) \quad \beta = 0.1 \]

\[ \frac{R_1}{R_1 + R_2} = 0.1 \quad \frac{R_2}{R_1} = 9 \]

c) \[ \text{Amount\_Feedback} := 20 \cdot \log(1 + A \cdot \beta) \]

\[ \text{Amount\_Feedback} = 60 \]

d) \[ V_s := 1 \quad V_o := A_f \cdot V_s \quad V_o = 10 \]

\[ V_f := \beta \cdot V_o \quad V_f = 0.999 \]

\[ V_i := V_s - V_f \quad V_i = 10 \times 10^{-4} \]

e) \[ A := 0.8 \cdot 10^4 \quad A_f := \frac{A}{1 + A \cdot \beta} \quad A_f = 9.998 \]

\[ \frac{10 - 9.998}{10} \cdot 100 = 0.02 \]
Some Properties of Negative Feedback

Gain Desensitivity

\[ A_f = \frac{A}{1 + A \cdot \beta} \]

deriving

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

dividing by \( A_f \) \( A_f = \frac{A}{1 + A \cdot \beta} \)

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

The percentage change in \( A_f \) (due to variations in some circuit parameter) is smaller than percentage change in \( A \) by the amount of feedback. For this reason the amount of feedback

\[ 1 + A \cdot \beta \]

is also known as the desensitivity factor.
Some Properties of Negative Feedback

Bandwidth Extension

High frequency response with a single pole

\[ A(s) = \frac{A_M}{1 + \frac{s}{\omega_H}} \]

\( A_M \) denotes the midband gain and \( \omega_H \) the upper 3-dB frequency.

\[ A_f(s) = \frac{A(s)}{1 + \beta \cdot A(s)} \]

\[ A_f(s) = \frac{A_M}{\left(1 + A_M \beta\right)} \]

\[ 1 + \frac{s}{\omega_H \cdot \left(1 + A_M \beta\right)} \]

\[ \omega_{Hf} = \omega_H \cdot \left(1 + A_M \beta\right) \]

\[ \omega_{Lf} = \frac{\omega_L}{1 + A_M \beta} \]
Oscillator
Oscillator principle

- Oscillators are circuits that generate periodic signals.
- An oscillator converts DC power from power supply to AC signals power spontaneously – without the need for an AC input source (Note: Amplifiers convert DC power into AC output power only if an external AC input signal is present.)
- There are several approaches to design of oscillator circuits. The approach to be discussed is related to the feedback using amplifiers. A frequency-selective feedback path around an amplifier is placed to return part of the output signal to the amplifier input, which results in a circuit called a linear oscillator that produces an approximately sinusoidal output.
- Under proper conditions, the signal returned by the feedback network has exactly the correct amplitude and phase needed to sustain the output signal.
The Barkhausen Criterion I

- Typically, the feedback network is composed of passive lumped components that determine the frequency of oscillation. So, the feedback is complex transfer function, hence denoted as \( \beta(f) \).

- We can derive the requirements for oscillation as follows: initially, assume a sinusoidal driving source with phasor \( X_{in} \) is present. But we are interested in derive the conditions for which the output phasor \( X_{out} \) can be non-zero even the input \( X_{in} \) is zero.

\[
X_{in} + \beta X_{out} = X_{in} + \beta(f) X_{out}
\]

The output of the amplifier block can be written as \( X_{out} = A(f)[X_{in} + \beta(f)X_{out}] \)

solve for \( X_{out} \), we obtain \( X_{out} = \frac{A(f)}{1 - A(f)\beta(f)} X_{in} \)

If \( X_{in} \) is zero, the only way the output can be non-zero is to have \( A(f)\beta(f) = 1 \).

- The above condition is know as Barkhausen Criterion.
The Barkhausen Criterion II

- The Barkhausen Criterion calls for two requirement for the loop gain. First, the magnitude of the loop gain must be unity. Second, the phase angle of the loop gain must be zero the frequency of oscillation. (e.g, if a non-inverting amplifier is used, then the phase angle of must be zero. For a inverting amplifier, the phase angle should be 180)

- In real oscillator design, we usually design loop-gain magnitude slightly larger than unity at the desired frequency of oscillation. Because a higher gain magnitude results in oscillations that grow in amplitude with time, eventually, the amplitude is clipped by the amplifier so that a constant-amplitude oscillation results.

- On the other hand, if exact unity loop gain magnitude is designed, a slight reduction in gain would result in oscillations that decays to zero.

- One important thing to note is that the initial input Xin is not needed, as in real circuits noise and transient signals associated with circuit turning on can always provide an initial signal that grows in amplitude as it propagates around the loop (assuming loop gain is larger than unity).
Contents:

• Introduction
• Classifications of Oscillators
• Circuit Analysis of a General Oscillator
• Hartley Oscillator
• Colpitts Oscillator
• RC Phase shift Oscillator
• Wien Bridge Oscillator
• Crystal Oscillator
• Applications of Oscillators
Objectives:

Different types of oscillators:
• An oscillator has a positive feedback with the loop gain infinite. Feedback-type sinusoidal oscillators can be classified as LC (inductor-capacitor) and RC (resistor-capacitor) oscillators.

- Tuned oscillator
- Hartley oscillator
- Colpitts oscillator
- Clapp oscillator
- Phase-shift oscillator
- Wien-bridge and
- Crystal oscillator
INTRODUCTION:

- An oscillator is an electronic system.
- It comprises active and passive circuit elements and sinusoidal produces repetitive waveforms at the output without the application of a direct external input signal to the circuit.
- It converts the dc power from the source to ac power in the load. A rectifier circuit converts ac to dc power, but an oscillator converts dc noise signal/power to its ac equivalent.
- The general form of a harmonic oscillator is an electronic amplifier with the output attached to a narrow-band electronic filter, and the output of the filter attached to the input of the amplifier.
- The oscillator analysis is done in two methods—first by a general analysis, considering all other circuits are the special form of a common generalized circuit and second, using the individual circuit KVL analysis.
Difference between an amplifier and an oscillator:

**Figure** Schematic block diagrams showing the difference between an amplifier and an oscillator.
CLASSIFICATIONS OF OSCILLATORS:

- The classification of various oscillators is shown in Table.

<table>
<thead>
<tr>
<th>Type of Oscillator</th>
<th>Frequency Range Used</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Audio-frequency oscillator</td>
<td>20 Hz – 20 kHz</td>
</tr>
<tr>
<td>2. Radio-frequency oscillator</td>
<td>20 kHz – 30 MHz</td>
</tr>
<tr>
<td>3. Very-high-frequency oscillator</td>
<td>30 MHz – 300 MHz</td>
</tr>
<tr>
<td>4. Ultra-high-frequency oscillator</td>
<td>300 MHz – 3 GHz</td>
</tr>
<tr>
<td>5. Microwave oscillator</td>
<td>3 GHz – 30 GHz</td>
</tr>
<tr>
<td>6. Millimeter wave oscillator</td>
<td>30 GHz – 300 GHz</td>
</tr>
</tbody>
</table>
CIRCUIT ANALYSIS OF A GENERAL OSCILLATOR:

- This section discusses the general oscillator circuit with a simple generalized analysis using the transistor, as shown in Fig.

- An impedance $z_1$ is connected between the base $B$ and the emitter $E$, an impedance $z_2$ is connected between the collector $C$ and emitter $E$. To apply a positive feedback $z_3$ is connected between the collector and the base terminal.

- All the other different oscillators can be analyzed as a special case of the generalized analysis of oscillator.

![Circuit Diagram](image-url)
CIRCUIT ANALYSIS OF A GENERAL OSCILLATOR:

- The above generalized circuit of an oscillator is considered using a simple transistor-equivalent circuit model. The current voltage expressions are expressed as follows:

\[ v_1 = h_i i_1 + h_r v_2 = h_i i_1 \]

As the numerical value of \( h_r v_2 \) is negligible:

\[ v_1 = h_i i_1 \]

\[ i_2 = h_f i_1 + h_0 v_2 = h_f i_1 \]

As the numerical value of \( h_0 v_2 \) negligible the Eq. (12-3) can be written as:

\[ i_2 = h_f i_1 \]

Applying KVL at loop (1) of Fig. by considering that current through the impedance \( z_1 \) is \( (i_1 - i_3) \), we get:

\[ v_1 + z_1 (i_1 - i_3) = 0 \]

or,

\[ v_1 = -z_1 (i_1 - i_3) = z_1 (i_3 - i_1) \]

Substituting the value of voltage \( v_1 \) from Eq. (12-2) in Eq. (12-5) we get:

\[ h_i i_1 + z_1 i_1 - z_1 i_3 = 0 \]

or,

\[ i_1 (h_i + z_1) - z_1 i_3 = 0 \]

Applying KVL at loop (3) by considering voltage across the impedance \( z_2 \):

\[ v_2 + z_2 (i_3 + i_2) = 0 \]
CIRCUIT ANALYSIS OF A GENERAL OSCILLATOR:

Substituting the value of current $i_2$ we get:

$$v_2 = -z_2(h_1 i_1 + i_3)$$

or,

$$z_2 h_1 i_1 + z_2 i_3 + v_2 = 0$$

Applying the KVL at loop (2) by considering voltage across $z_3$, we get,

$$i_3 z_3 + (i_2 + i_3) z_2 + (i_3 - i_1) z_1 = 0$$

or,

$$i_3 z_3 - v_2 + v_1 = 0$$

or,

$$i_3 z_3 = v_2 - v_1$$

Substituting the value of $v_1$ in Eq. we get:

$$i_3 z_3 = v_2 - h_1 i_1$$

or,

$$i_3 z_3 - v_2 + h_1 i_1 = 0$$

or,

$$-(v_2 - i_3 z_3 - h_1 i_1) = 0$$

or,

$$v_2 - h_1 i_1 - z_3 i_3 = 0$$
CIRCUIT ANALYSIS OF A GENERAL OSCILLATOR:

Eq. can be rewritten as:

\[ i_1(h_i + z_1) + 0. v_2 + (-z_1)i_3 = 0 \]
\[ -i_1z_2 h_f + 1. v_2 + z_2 i_3 = 0 \]
\[ -i_1 h_i + 1. v_2 + (-z_3)i_3 = 0 \]

Eliminating three variables \( i_1, v_2, i_3 \) using Camers rule, and from Eqs. , we get the following matrix:

\[
\begin{vmatrix}
(h_i + z_1) & 0 & -z_1 \\
z_2 h_f & 1 & z_2 \\
-h_i & 1 & -z_3 \\
\end{vmatrix} = 0
\]

or

\[ (h_i + z_1)[(-z_3 - z_2)] + 0 + (-z_1)[z_2 h_f + h_i] = 0 \]

or

\[ -z_3 h_i - z_2 h_i - z_1 z_3 - z_1 z_2 - z_1 z_2 h_f - z_1 h_i = 0 \]

or

\[ -h_i[z_3 + z_2 z_1] - z_1 z_2 [1 + h_f] - z_1 z_3 = 0 \]

or

\[ h_i[R + jx] + z_1 z_2 [1 + h_f] + z_1 z_3 = 0 \]
CIRCUIT ANALYSIS OF A GENERAL OSCILLATOR:

Let,

$$z_1 = R_1 + jx_1 = jx_1$$

$$z_2 = R_2 + jx_2 = jx_2$$

$$z_3 = R_3 + jx_3 = jx_3$$

$$\Theta \quad R_1 = x_1$$

$$R_2 = x_2$$

& $$R_3 = x_3$$

By adding, we get:

$$(z_1 + z_2 + z_3) = (R + jx)$$

where, $$R = (R_1 + R_2 + R_3)$$ is not negligible in comparison with $$x = x_1 + x_2 + x_3$$ as we shall see $$x = 0$$ at frequency of oscillation.

$$\therefore$$

$$z_1z_2(h_f + 1) + (z_1 + z_2 + z_3)h_i + z_1z_3 = 0$$

$$-x_1x_2(h_f + 1) + (R + jx)h_i - x_1x_3 = 0$$

$$-x_1[x_2(h_f + 1) + x_3] + (R + jx)h_i = 0$$
CIRCUIT ANALYSIS OF A GENERAL OSCILLATOR:

Equating imaginary parts \[\Theta jx_1jx_2 = -x_1x_2\]:

\[jxh_i = 0\]  

\[\therefore \quad x = 0\]

\[x_1 + x_2 + x_3 = 0\]  

(+ve) inductive impedance

(−ve) capacitive impedance

Equating real parts we get:

\[-x_1x_2[h_f + 1] + R \cdot h_i - x_1x_3 = 0\]

\[x_1x_2h_f + x_1(x_2 + x_3) - R \cdot h_i = 0\]

From the Eq we get:

\[x_2 + x_3 = -x_1\]

Substituting the value of Eq we get:

\[x_1x_2h_f - x_1^2 - R \cdot h_i = 0\]

\[h_f = \frac{x_1}{x_2} + \frac{R \cdot h_i}{x_1x_2}\]

This is the general condition for oscillation for an oscillator.

Different types of oscillator circuits with different configurations can be analysed through this general method. This makes the analysis simpler.
Hartley Oscillator:

Hartley oscillator contains two inductors and one capacitor, as shown in Fig. where, $x_1$ and $x_2$ are inductances, and $x_3$ is a capacitance, i.e., $x_1 = \omega L_1$, $x_2 = \omega L_2$, $x_3 = -1/\omega C$.

Substituting the values in Eq. we get the condition for oscillation, considering $R$ is small.

$$h_f = \frac{\omega L_1}{\omega L_2} + \frac{R \cdot h_i}{\omega^2 L_1 L_2}$$

**Figure** Hartley Oscillator
Hartley Oscillator:

Substituting the values in Eq. we get the condition for oscillation, considering \( R \) is small.

\[
h_f = \frac{\omega L_1}{\omega L_2} + \frac{R \cdot h_i}{\omega^2 L_1 L_2}
\]

\[
h_f = \frac{L_1}{L_2}
\]

\[
h_f = \frac{L_1}{L_2} + \frac{RCH_i}{L_{11}}
\]

Where

\[
L_{11} = \frac{L_1 L_2}{L_1} + L_2
\]

\[
L_{11} = \frac{L_1 L_2}{L_1} + L_2
\]

\[
L_{11}(L_1 + L_2) = L_1 L_2
\]

\[
L_{11} \times \frac{1}{\omega^2 C} = L_1 L_2
\]

\[
\therefore \frac{L_1}{L_2} + \frac{R_h}{\omega^3 L_1 L_2} = \frac{L_1}{L_2} + \frac{R_h C}{L_{11}}
\]
Colpitts Oscillator:

\[ R = \frac{C_2}{C_1} + Rh_i \frac{1}{L} (C_1 + C_2) Rh_i \]

\[ R = \frac{C_2}{C_1} \left[ \text{neglecting} \frac{Rh_i}{L} (C_1 + C_2) \right] \]

The circuit diagram of Colpitts oscillator is shown in Fig.
Colpitts Oscillator:

Colpitt oscillator contains two capacitors and one inductor, as shown in Fig. $X_1$ and $X_2$ are capacitances, $X_3$ is inductance, $Z_1$ and $Z_2$ are capacitors, $C_1$ and $C_2$ are capacitances, and $Z_3$ is an inductor of inductance $L$.

\[ X_1 = -\frac{1}{\omega C_1} \]

\[ X_2 = -\frac{1}{\omega C_2} \]

\[ X_3 = \omega L \]

\[ X_1 + X_2 + X_3 = 0 \]

\[ -\frac{1}{\omega C_1} - \frac{1}{\omega C_2} + \omega L = 0 \]

\[ \frac{1}{\omega} \left( \frac{1}{C_1} + \frac{1}{C_2} \right) = \omega L \]
Colpitts Oscillator:

\[
\frac{1}{L} \left( \frac{1}{C_1} + \frac{1}{C_2} \right) = \omega^2, \quad \omega = \sqrt{\frac{1}{L} \left( \frac{1}{C_1} + \frac{1}{C_2} \right)}
\]

Frequency of oscillation:

\[
2\pi f = \frac{1}{\sqrt{LC}} \implies f = \frac{1}{2\pi \sqrt{LC}}
\]

Where,

\[
\frac{1}{C'} = \frac{1}{C_1} + \frac{1}{C_2}
\]

\[
h_f = \frac{X_1}{X_2} + \frac{Rh_i}{X_1X_2}
\]

Therefore, condition for oscillation:

\[
h_f = \frac{C_2}{C_1} + Rh_i \omega^2 C_1 C_2
\]

\[
= \frac{C_2}{C_1} + R_m \omega^2 C_1 C_2
\]

\[R = \text{Resistance of the coil 2}\]

\[
R = \frac{C_2}{C_1} + Rh_i \frac{1}{L} \cdot \frac{C_1 + C_2}{C_1 \cdot C_2} \cdot C_1 C_2 \quad \therefore \quad \omega^2 = \frac{1}{L} \left( \frac{1}{C_1} + \frac{1}{C_2} \right)
\]
Phase-Shift Oscillator:

Eliminating $i_1, i, i^1$,

$$
\begin{bmatrix}
  i_1 & i & i^1 \\
  (2R + jx_c) & 0 & -R \\
  Rh_f & (2R + jx_c) & -R \\
  -R & -R & (2R + jx_c)
\end{bmatrix}
$$
Phase-Shift Oscillator:

The circuit diagram of a phase-shift oscillator with three pairs of RC combination is shown in Fig. The equivalent circuit representation of phase-shift oscillator is shown in Fig. By applying KVL in the circuit in Fig. we have the mesh \( \text{ABCHIJ} \) at loop (2).

\[
(i + h_f i_1) R + (i - i^1) R + \frac{i}{j\omega C} = 0
\]

\[
\left(2R + \frac{1}{j\omega C}\right) i + R h_f i_1 - R i^1 = 0
\]

\[
(2R + jx_c) i + R h_f i_1 - R i^1 = 0
\]

At mesh CDGH [at loop (3)]:

\[
(i^1 - i) R + \frac{1}{j\omega C} i^1 + (i^1 - i) R = 0
\]

\[
(2R + jx_c) i^1 - Ri - Ri_1 = 0
\]

At mesh CDEFGH [at loop (4)]:

\[
(i_1 - i^1) R + jx_c i_1 + Ri_1 = 0
\]

\[
(2R + jx_c) i_1 - Ri^1 = 0
\]
Phase-Shift Oscillator:

![Equivalent circuit representation of a phase-shift oscillator](image)

**Figure** Equivalent circuit representation of a phase-shift oscillator

Dividing each element of the determinant by $R$:

$$
\begin{vmatrix}
\frac{1}{R} & R(2 + j\frac{x_c}{R}) & 0 & -\frac{R}{R} \\
R_{\text{out}} & R(2 + j\frac{x_c}{R}) & -\frac{R}{R} & R(2 + j\frac{x_c}{R}) \\
-\frac{R}{R} & -\frac{R}{R} & \frac{R}{R} & R(2 + j\frac{x_c}{R}) \\
\end{vmatrix} = 0
$$

Let

$$\frac{X_c}{R} = a$$

$$
\begin{vmatrix}
2 + ja & 0 & -1 \\
h_f & 2 + ja & -1 \\
-1 & -1 & (2 + ja) \\
\end{vmatrix} = 0
$$
Phase-Shift Oscillator:

Let \( \frac{X_C}{R} = a \)

\[
\begin{vmatrix}
(2 + ja) & 0 & -1 \\
-1 & (2 + ja) & -1 \\
(2 + ja) & -1 & (2 + ja)
\end{vmatrix} = 0
\]

\[
(2 + ja) [(2 + ja)^2 - 1] + 0 + (-1) [-h_f + 2 + ja] = 0
\]

\[
(2 + ja) [4 + 4ja - a^2 - 1] + h_f - 2 - ja = 0
\]

\[
8 + 8ja - 2a^2 - 2 + 4ja - 4a^2 - ja^3 - ja + h_f - 2 - ja = 0
\]

\[
-j a^3 + 8 + 12ja - 6a^2 - 4 - 2ja + h_f = 0
\]

\[
\therefore \text{Equating the imaginary parts:}
\]

\[
j (-a^3 - 2a + 12a) = 0
\]

\[
a (10 - a^2) = 0
\]

\[
a^2 - 10 = 0
\]

\[
\therefore a = \sqrt{10}
\]
Phase-Shift Oscillator:

\[ \frac{X_C}{R} = \sqrt{10} \]
\[ \frac{X_C^2}{R^2} = 10 \]
\[ \frac{1}{\omega^2 C^2 R^2} = 10 \]
\[ \omega^2 = \frac{1}{10 C^2 R^2} \]
\[ \omega = \frac{1}{\sqrt{10} CR} \]

*Figure* Equivalent diagram of a phase-shift oscillator
Phase-Shift Oscillator:

\[ f = \frac{1}{2\pi \sqrt{10 \ CR}} \]

\[ 8 - 6a^2 - 4 + h_{fe} = 0 \]

\[ h_{fe} = 4 + 6a^2 - 8 = 4 + 6.10 - 8 \]

\[ = 4 + 60 - 8 \]

\[ = 56 \]

For sustained oscillations, \( h_{fe} \) of 56 for \( R = R_L \)

The equivalent diagram of a phase-shift oscillator is shown in Fig.
Wien-Bridge Oscillator:

Figure Wien-bridge oscillator with an amplifier
Wien-Bridge Oscillator:

Wein-bridge oscillator is the series and parallel combination of a resistance $R$ and a capacitor $C$. According to Barkhausen criteria, $A, \beta = 1$.

Since $A, \beta = 1$,

$$\beta = \frac{1}{A_v} = \frac{v_x}{v_0} = \frac{v_{zf}}{(z_1 + z_2)i}$$

$$A_v = \frac{1}{\beta} = \frac{z_1 + z_2}{z_2} = 1 + \frac{z_1}{z_2}$$

$$z_1 = R + jx_1 \text{ [series combination]}$$

$$\frac{1}{z_2} = \frac{1}{R_2} + \frac{1}{jx_2} \text{ [parallel combination]}$$

$$A = 1 + (R_1 + jx_1) \left( \frac{1}{R_2} + \frac{1}{jx_2} \right)$$

$$= 1 + \left( \frac{R_1}{R_2} + \frac{x_1}{x_2} \right) + j \left( \frac{x_1}{R_2} - \frac{R_1}{x_2} \right)$$
The two-stage $RC$ coupled amplifier can be used by equating real and imaginary parts. Considering only the real parts, we get:

$$A = 1 + \frac{R_1}{R_2} + \frac{x_1}{x_2}$$

Considering only the imaginary parts, we get:

$$\frac{x_1}{R_2} - \frac{R_1}{X_2} = 0$$

$X_1X_2 = R_1R_2$ (frequency of oscillation)

$$R_1R_2 = \frac{1}{w^2c_1c^2}$$

$$w^2 = \frac{1}{C_1C_2R_1R_2}$$
Wien-Bridge Oscillator:

If $R_1 = R_2 = R$  &  $C_1 = C_2 = C$

\[ A = 1 + 1 + 1 = 3 \]

And,

\[ w^2 = \frac{1}{C^2 R^2} \Rightarrow w = \frac{1}{CR} \]

\[ f = \frac{1}{2\pi CR} \]

At balance condition:

\[ \frac{R_3}{R_4} = \frac{Z_1}{Z_2} \text{ (for oscillation)} \]
Wien-Bridge Oscillator:

From the circuit diagram of the wien-bridge oscillator, as given in Fig. we get:

\[
\frac{R_3}{R_4} = \left( \frac{R_1}{j\omega C_1} \right) \left( \frac{1}{R_2} + j\omega C_2 \right)
\]

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

Equating imaginary parts we get:

\[
\omega C_2 R_1 = \frac{1}{\omega C_1 R_2}
\]

\[
\omega^2 = \frac{1}{C^2 R^2}
\]

\[\therefore R_1 = R_2 = R \quad \text{and} \quad C_1 = C_2 = C\]

\[\therefore \frac{R_3}{R_4} = \frac{R_1}{R_2} + \frac{C_2}{C_1}\]

\[
\frac{R_3}{R_4} = \frac{R}{R} + \frac{C}{C} = 1 + 1 = 2
\]
Wien-Bridge Oscillator:

• **Advantages of Wien-Bridge Oscillator:**
  • 1. The frequency of oscillation can be easily varied just by changing $RC$ network
  • 2. High gain due to two-stage amplifier
  • 3. Stability is high

• **Disadvantages of Wien-Bridge Oscillator**
  • The main disadvantage of the Wien-bridge oscillator is that a high frequency of oscillation cannot be generated.
CRYSTAL OSCILLATOR:

- Crystal oscillator is most commonly used oscillator with high-frequency stability. They are used for laboratory experiments, communication circuits and biomedical instruments. They are usually, fixed frequency oscillators where stability and accuracy are the primary considerations.
- In order to design a stable and accurate LC oscillator for the upper HF and higher frequencies it is absolutely necessary to have a crystal control; hence, the reason for crystal oscillators.
- Crystal oscillators are oscillators where the primary frequency determining element is a quartz crystal. Because of the inherent characteristics of the quartz crystal the crystal oscillator may be held to extreme accuracy of frequency stability. Temperature compensation may be applied to crystal oscillators to improve thermal stability of the crystal oscillator.
- The crystal size and cut determine the values of L, C, R and C'. The resistance R is the friction of the vibrating crystal, capacitance C is the compliance, and inductance L is the equivalent mass. The capacitance C' is the electrostatic capacitance between the mounted pair of electrodes with the crystal as the dielectric.
Circuit Diagram of CRYSTAL OSCILLATOR:

Figure Circuit of a crystal oscillator
Circuit Diagram of CRYSTAL OSCILLATOR:

(a) Symbol of a vibrating piezoelectric crystal (b) Its equivalent electrical circuit

Figure Reactance vs. frequency graph
Circuit Analysis of CRYSTAL OSCILLATOR:

The circuit of Fig. 12 has two resonant frequencies. At the series resonant frequency $f_s$ the reactance of the series $LC$ arm is zero, that is:

$$\omega_s L - \frac{1}{\omega_s C} = 0$$

or

$$\omega_s = \frac{1}{\sqrt{LC}}$$

$\omega_p$ is the parallel resonant frequency of the circuit greater than $\omega_s$ where:

$$\left( \omega_p L - \frac{1}{\omega_p C} \right) = \frac{1}{\omega_p C'}$$

or

$$\omega_p^2 = \frac{1}{2} \left( \frac{1}{C} + \frac{1}{C'} \right)$$

or

$$\omega_p = \sqrt{\frac{1}{2} \left( \frac{1}{C} + \frac{1}{C'} \right)}$$

Therefore, $\omega_p$ and $\omega_s$ are as shown in Fig. 12-12. At the parallel, resonant frequency, the impedance offered by the crystal to the internal circuit is very high.

The resonant frequencies of a crystal vary inversely as the thickness of the cut.

$$f = \frac{1}{l}$$
Oscillators are a common element of almost all electronic circuits. They are used in various applications, and their use makes it possible for circuits and subsystems to perform numerous useful functions.

In oscillator circuits, oscillation usually builds up from zero when power is first applied under linear circuit operation.

The oscillator’s amplitude is kept from building up by limiting the amplifier saturation and various non-linear effects.

Oscillator design and simulation is a complicated process. It is also extremely important and crucial to design a good and stable oscillator.

Oscillators are commonly used in communication circuits. All the communication circuits for different modulation techniques—AM, FM, PM—the use of an oscillator is must.

Oscillators are used as stable frequency sources in a variety of electronic applications.

Oscillator circuits are used in computer peripherals, counters, timers, calculators, phase-locked loops, digital multi-metres, oscilloscopes, and numerous other applications.
### POINTS TO REMEMBER:

1. Oscillator converts dc to ac.
2. Oscillator has no input signal.
3. Oscillator behaviour is opposite to that of a rectifier.
4. The conditions and frequencies of oscillation are classified as:

<table>
<thead>
<tr>
<th>Types of Oscillator</th>
<th>Condition of Oscillation</th>
<th>Frequency of Oscillation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hartley Oscillator</td>
<td>$h_r = \frac{\omega L_1}{\omega L_2} + \frac{R h_i}{\omega^2 L_1 L_2}$</td>
<td>$f = \frac{\omega}{2\pi} = \frac{1}{2\pi} \left[ (h_{re} L_1 L_2 h_{re}) + C (L_1 + L_2) \right]^{1/2}$</td>
</tr>
<tr>
<td></td>
<td>Simple,</td>
<td>$f = \frac{1}{2\pi \sqrt{C (L_1 + L_2)}} = \frac{1}{2\pi \sqrt{LC'}}$</td>
</tr>
<tr>
<td>Colpitts Oscillator</td>
<td>$h_r = \frac{C_2}{C_1} + Rh_i \cdot \omega^2 C_1 C_2$</td>
<td>$f = \frac{\omega}{2\pi} = \frac{1}{2\pi} \left( \frac{h_{re}}{h_{re} C_1 C_2} + \frac{1}{L C_1} + \frac{1}{L C_2} \right)^{1/2}$</td>
</tr>
<tr>
<td>Phase-Shift Oscillator</td>
<td>The transistor should have an $h_{re}$ of 56 when $RL = R$.</td>
<td>$f = \frac{1}{2\pi \sqrt{10 CR}}$</td>
</tr>
<tr>
<td>Wein-Bridge Oscillator</td>
<td>$\frac{R_1}{R_2} = 2$</td>
<td>$f = \frac{\omega}{2\pi} = \frac{1}{2\pi RC}$</td>
</tr>
<tr>
<td>Crystal Oscillator</td>
<td>—</td>
<td>$f_p = \frac{\omega_p}{2\pi} = \frac{1}{2\pi} \sqrt{\frac{C + C'}{LCC'}}$</td>
</tr>
</tbody>
</table>
IMPORTANT FORMULAE:

1. General condition for oscillation for an oscillator:
   \[ h_f = \frac{x_1}{x_2} + \frac{R_{hi}}{x_1x_2} \]

2. Frequency of oscillation for a Hartley oscillator:
   \[ f = \frac{1}{2\pi} \sqrt{C(L_1 + L_2)} \]

3. Condition for oscillation for a Colpitts oscillator:
   \[ h_f = \frac{C_2}{C_1} + R h_i \omega^2 C_1 C_2 \]

4. Frequency of oscillation for a phase-shift oscillator:
   \[ f = \frac{1}{2\pi} \sqrt{10 CR} \]

5. Frequency of oscillation for a Wien-Bridge oscillator:
   \[ f = \frac{1}{2\pi CR} \]

6. If the feedback signal aids the externally applied input signal, the overall gain is given by:
   \[ Af = \frac{A}{1 - A\beta} \]

7. Value of M required for sustained oscillations is given by:
   \[ M = \frac{R_B}{h_{fe}} (CR + h_{oe} L) + CR \frac{h_{ie}}{h_{fe}} + L \frac{\Delta h_e}{h_{fe}} \]

8. Oscillation frequency of a Clapp oscillator is given by:
   \[ f_0 = \frac{1}{2\pi} \sqrt{\frac{1}{L} \left( \frac{1}{C_0} + \frac{1}{C_1} + \frac{1}{C_2} \right)} \]

9. Condition for sustained oscillation for a phase-shift oscillator is given by:
   \[ h_{fe} = 23 + 29 \frac{R}{R_L} + 4 \frac{R_L}{R} \]