Feedback & Oscillator Circuits

Feedback Concepts:

A typical feedback connection is shown in Figure. The input signal, $V_s$ is applied to a mixer network, where it is combined with a feedback signal, $V_f$. The difference of these signals, $V_i$, is then the input voltage to the amplifier. A portion of the amplifier output, $V_o$ is connected to the feedback network ($\beta$), which provides a reduced portion of the output as feedback signal to the input mixer network.

Positive Feedback: the feedback signal is of the same polarity to the input signal.

Negative Feedback: the feedback signal is of opposite polarity to the input signal, as shown in Figure.

While negative feedback results in reduced overall voltage gain, a number of improvements are obtained, among them being:

1) Higher I/P impedance.
2) Better stabilized voltage gain.
3) Improved frequency response.
4) Lower output impedance.
5) Reduced noise.
6) More linear operation.
Feedback Connection Types:

1) Voltage-series feedback.

2) Voltage-shunt feedback

3) Current-series feedback

4) Current-shunt feedback
Effect of Feedback:

1) **Effect of Feedback on the gain** (Voltage –Series Feedback)

If there is no FB ($V_f = 0$), the voltage gain of the amplifier stage is

$$A = \frac{V_o}{V_z} = \frac{V_o}{V_i}$$

If feedback signal, $V_f$ is connected in series with the input, then

$$V_i = V_z - V_f$$

Since

$$V_o = AV_i = A(V_z - V_f) = AV_z - AV_f = AV_z - A(\beta V_o)$$

then

$$V_o = (1 + \beta A)V_o = AV_z$$

So the overall voltage gain with feedback is

$$A_f = \frac{V_o}{V_z} = \frac{A}{1 + \beta A}$$

Which shows that the gain with feedback is the amplifier gain **reduced** by the factor $(1 + \beta A)$. 
2) **Effect of Feedback on I/P Impedance** (Voltage –Series Feedback)
A more detailed voltage-series feedback connection is shown in Figure.

The input impedance with series feedback is seen to be the value of the input impedance without feedback multiplied by the factor \((1 + \beta A)\).

3) **Effect of Feedback on O/P Impedance** (Voltage –Series Feedback)
The O/P impedance is determined by applying a voltage, \(V\), resulting in a current, \(I\), with \(V_s\) shorted out (\(V_s = 0\)). The voltage \(V\) is then

\[
V = IZ_o + AV_i
\]

For \(V_s = 0\),

\[
V_i = -V_f
\]

So that

\[
V = IZ_o - AV_f = IZ_o - A(\beta V)
\]

Rewriting the equation as
\[ V + \beta AV = IZ_o \]

\[ Z_{of} = \frac{V}{I} = \frac{Z_o}{1 + \beta A} \]

Which shows that with voltage –series feedback the output impedance is reduced from that without feedback by the factor \((1 + \beta A)\).

**Example:**

Determine the voltage gain, input, and output impedance with feedback for voltage series feedback having \(A = -100\), \(R_i = 10 \, \text{K}\Omega\), \(R_o = 20 \, \text{K}\Omega\) for feedback of: a) \(\beta = -0.1\) and b) \(\beta = -0.5\).
Effect of Negative Feedback on Gain and Bandwidth:

For $\beta A \gg 1$, the overall gain with negative feedback is shown to be:

$$Af = \frac{A}{1 + \beta A} \approx \frac{A}{\beta A} = \frac{1}{\beta}$$

The Figure shows that the amplifier with $-ve$ FB has more bandwidth ($B_f$) than the amplifier without FB ($B$). The FB amplifier has a higher upper 3-dB frequency and smaller lower 3-dB frequency.

Gain Stability with Feedback:

Differentiating the eqn.

$$Af = \frac{V_o}{V_z} = \frac{A}{1 + \beta A}$$

Leads to:

$$\left| \frac{dA_f}{Af} \right| = \frac{1}{1 + \beta A} \left| \frac{dA}{A} \right|$$

$$\left| \frac{dA_f}{Af} \right| \approx \frac{1}{\beta A} \left| \frac{dA}{A} \right| \quad \text{for} \quad \beta A \gg 1$$

This shows that the relative change in gain with FB is reduced by the factor $\beta A$ compared to that without FB.
Example:

If an amplifier with gain of -1000 and feedback of $\beta = -0.1$ has a gain change of 20% due to temperature.

Calculate the change in gain of the feedback amplifier.

Using the above eqn.

$$\left| \frac{dA_f}{A_f} \right| \approx \left| \frac{1}{\beta A} \right| \left| \frac{dA}{A} \right| = \left| \frac{1}{-0.1(-1000)} \right| (20\%) = 0.2\%$$

The improvement is 100 times. Thus while the amplifier gain changes from $A = 1000$ by 20%, the gain with FB changes from $A_f = 10$ by only 0.2%.

Hint:

For the FET small-signal model, recall that the gate-to-source voltage controls the drain-to-source channel) current thro' a relationship known as Shockley's eqn.

$$I_D = I_{DSS}(1 - V_{GS}/V_P)^2$$

The change in the drain current that will result from a change in the gate-to-source voltage can be determined using the transconductance factor $g_m$.

$$g_m = \frac{\Delta I_D}{\Delta V_{GS}}$$
**Practical Feedback circuits:**

**Voltage-Series Feedback:** The Figure shows a FET amplifier stage with voltage-series FB. The FB voltage $V_f$ is connected in series with the source signal $V_s$, their difference is the input signal $V_i$.

Without feedback the amplifier gain is

$$ A = \frac{V_o}{V_i} = -g_m R_L $$

Where $R_L$ is the parallel combination of resistors $R_D$, $R_o$, $(R_1 + R_2)$.

The feedback network provides a FB factor of

$$ \beta = \frac{V_f}{V_o} = \frac{-R_2}{R_1 + R_2} $$

The gain with negative feedback:

$$ A_f = \frac{A}{1 + \beta A} = \frac{-g_m R_L}{1 + [R_2 R_L/(R_1 + R_2)] g_m} $$

If $\beta A \gg 1$, we have

$$ A_f \approx \frac{1}{\beta} = -\frac{R_1 + R_2}{R_2} $$
**Example:** For the FET amplifier circuit of the Figure above having the following values:

\( R_1 = 80 \, \text{k}\Omega \), \( R_2 = 20 \, \text{k}\Omega \), \( R_o = 10 \, \text{k}\Omega \), \( R_D = 10 \, \text{k}\Omega \), and \( g_m = 4000 \, \mu\text{S} \).

Calculate the gain without and with feedback.

\[
R_L \approx \frac{R_o R_D}{R_o + R_D} = \frac{10 \, \text{k}\Omega \times 10 \, \text{k}\Omega}{10 \, \text{k}\Omega + 10 \, \text{k}\Omega} = 5 \, \text{k}\Omega
\]

Neglecting 100 k\Omega resistance of \( R_1 \) and \( R_2 \) in series

\( A = -g_m R_L = -(4000 \times 10^{-6} \, \mu\text{S})(5 \, \text{k}\Omega) = -20 \)

The feedback factor is

\[
\beta = \frac{-R_2}{R_1 + R_2} = \frac{-20 \, \text{k}\Omega}{80 \, \text{k}\Omega + 20 \, \text{k}\Omega} = -0.2
\]

The gain with feedback is

\[
A_f = \frac{A}{1 + \beta A} = \frac{-20}{1 + (-0.2)(-20)} = \frac{-20}{5} = -4
\]

The Figure shows a voltage-series feedback connection using Op-Amp. The gain of the amplifier \( A \) (without FB) is reduced by the feedback factor:

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

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**Exercise:**

Calculate the amplifier gain with FB of the op-amp of gain \( A = 10^6 \), and resistances \( R_1 = 1.8 \, \text{k}\Omega \), \( R_2 = 200\Omega \).

Check: \( \beta = 0.1 \), \( A_f = 9.999 \) (N.B. \( \beta A = 10,000 >> 1 \), \( A_f = 1/\beta = 10 \)).
**Oscillator Operation**

Consider the FB circuit of Figure. When the switch at the amplifier I/P, no oscillation occurs. Consider that we have a fictitious voltage at the amplifier I/P (Vi), this results in an O/P voltage $V_o = AV_i$ after the amplifier stage and in a voltage $V_f = \beta(AV_i)$ after the feedback stage.

Thus, we have a FB voltage $V_f = \beta AV_i$, where $\beta A$ is referred to as the **loop gain**. If the circuits of the amplifier and the feedback network provide $\beta A$ of correct magnitude and phase, $V_f$ can be made equal to $V_i$.

![Oscillator Diagram](image)

Then, when the switch is closed and the fictitious voltage $V_i$ is removed, the circuit will continue operating since the FB voltage is sufficient to drive the amplifier and feedback circuits resulting in a proper I/P voltage to sustain the loop operation. The O/P waveform will still exist after the switch is closed if the following condition is met:

$$\beta A = 1$$

In reality, no I/P signal is needed to start the oscillator going. In practice, $\beta A = 1$ is made greater than 1 and the system is started oscillating by amplifying noise voltage, which is always present. The resulting waveforms are never exactly sinusoidal. However, the closer the value $\beta A$ is to exactly 1, the more nearly sinusoidal is the waveform. The following Figure shows the buildup of steady-state oscillation.
Another way of seeing how the FB circuit provides operation as an oscillator is obtained from the feedback equation:

$$A_f = \frac{A}{1 + \beta A}$$

When $\beta A = -1$ or magnitude 1 at a phase angle of $180^\circ$, the denominator becomes 0 and the gain with FB, $A_f$, becomes $\infty$. Thus, an infinitesimal signal (noise) can provide a measurable O/P voltage, and the circuit acts as an oscillator even without an i/p signal.
Concentrating our attention on the phase-shift network, we are interested in the attenuation of the network at the frequency at which the phase shift is exactly $180^\circ$. Using network analysis, we find that:

\[ f = \frac{1}{2\pi RC\sqrt{6}} \]

\[ \beta = \frac{1}{29} \]

And the phase shift is $180^\circ$.

For the loop gain $\beta A$ to be greater than unity, the gain of the amplifier stage must be greater than $1/\beta$ or 29:

\[ A > 29 \]
FET Phase-Shift Oscillator:

The amplifier gain magnitude is calculated from:

\[
|A| = g_m R_L
\]

\[
R_L = \frac{R_D r_d}{R_D + r_d}
\]

The output impedance of the amplifier stage given by RL should be small compared to the impedance seen looking into the FB network so that no attenuation due to loading occurs.

**Example:**

Design a phase-shift oscillator using a FET having \( g_m = 5000 \ \mu S \), \( r_d = 40 \ \text{k}\Omega \), and feedback circuit value of \( R = 10 \ \text{k}\Omega \). Select the value of C for oscillator operation at a KHz and RD for \( A > 29 \) to ensure oscillator action.
Transistor Phase-Shift Oscillator:

The circuit shows a BJT version of phase-shift oscillator. In this connection, the FB signal is coupled through the FB resistor $R'$ in series with the amplifier stage I/P resistance ($R_i$).

Analysis of the ac circuit provides the following equation for the oscillator frequency:

$$f = \frac{1}{2\pi RC} \frac{1}{\sqrt{6 + 4(R_C/R)}}$$

For the loop gain ($\beta A$) to be $> 1$, the requirement on the current gain of the transistor is found to be

$$h_{fe} > 23 + 29 \frac{R}{R_C} + 4 \frac{R_C}{R}$$
**Example:** For the BJT phase-shift oscillator circuit and for $R = 8 \, \text{K}\Omega$, $C = 100 \, \text{pF}$, and $R_c = 20 \, \text{K}\Omega$, 

a) Calculate the oscillator frequency.

b) Find the requirement on the current gain, $h_{fe}$ of the transistor for oscillation.
Wien Bridge Oscillator:

The basic bridge connection: R1, R2 and capacitors C1 and C2 form the frequency-adjustment elements, while resistors R3 and R4 form part of the FB path.

The op-amp O/P is connected as the bridge I/P at point \( a \) and \( c \). The bridge circuit O/P at points \( b \) and \( d \) is the input to the op-amp.

Neglecting loading effects of the op-amp I/P and O/P impedances, the analysis of the bridge circuit results in:

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

\[
f_o = \frac{1}{2\pi \sqrt{R_1C_1R_2C_2}}
\]

If, in particular, \( R_1 = R_2 = R \) and \( C_1 = C_2 = C \), the resulting oscillator frequency, and the ratio \( R_3/R_4 \) are:

\[
f_o = \frac{1}{2\pi RC}
\]

\[
\frac{R_3}{R_4} = 2
\]
Thus a ratio of $(R3/R4) > 2$ will provide sufficient loop gain for the circuit to oscillate at the frequency calculated from the expression of $f_o$.

**Example:** Calculate the resonant frequency of the Wien bridge oscillator of Figure.
**Example**: Design the RC elements of a Wien bridge oscillator in the following Figure for operation at $f_o = 10$ KHz.
**Tuned Oscillator Circuit** (Tuned I/P, Tuned O/P circuits)

A variety of circuits can be built using that shown in Figure by providing tuning in both the I/P and O/P sections of the circuit. Analysis of the circuit in Figure reveals the following types of oscillators are obtained when the reactance elements are as designated:

(Basic configuration
Of resonant Oscillator circuit)

<table>
<thead>
<tr>
<th>Oscillator Type</th>
<th>$X_1$</th>
<th>$X_2$</th>
<th>$X_3$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Colpitts oscillator</td>
<td>$C$</td>
<td>$C$</td>
<td>$L$</td>
</tr>
<tr>
<td>Hartley oscillator</td>
<td>$L$</td>
<td>$L$</td>
<td>$C$</td>
</tr>
<tr>
<td>Tuned input, tuned output</td>
<td>$LC$</td>
<td>$LC$</td>
<td>—</td>
</tr>
</tbody>
</table>
**Colpitts Oscillator**

**FET COLPITTS OSCILLATOR**

A practical version of an FET Colpitts oscillator is shown in Figure. The circuit is basically the same form as shown in the basic configuration with the addition of the components needed for dc bias of the FET amplifier. The oscillator frequency can be found to be:

\[
f_o = \frac{1}{2\pi \sqrt{LC_{eq}}}
\]

\[
C_{eq} = \frac{C_1 C_2}{C_1 + C_2}
\]

---

**Example:**

For the FET Colpitts oscillator as in Figure and the following circuit values, determine the oscillation frequency:

C1 = 750 pF, C2 = 2500 pF, and L = 40 μH.

**Solution:** check \(C_{eq} = 576.9\) pF.

Check \(f_o = 1.048 \text{ MHz}\).
IC Colpitts Oscillator: Again the op-amp provides the basic amplification needed while the oscillator frequency is set by an LC feedback network of a Colpitts configuration. The oscillator frequency is given by the same equation as before.

Example: For the IC Op-amp Colpitts oscillator and the following circuit values, determine the oscillation frequency:

\[ C_1 = 2000 \text{ pF}, \ C_2 = 2000 \text{ pF}, \text{ and } L = 20 \mu \text{H}. \]

Solution:

Check \( C_{eq} = 1000 \text{ pF} \),

Check \( f_o = 1.125 \text{ MHz} \).
**Hartley Oscillator:**

The elements in the basic resonant circuit $X_1$ and $X_2$ are (inductors) and $X_3$ (capacitor).

An FET Hartley oscillator circuit is shown in Figure.

![Hartley Oscillator Circuit](image)

Note that inductors $L_1$ and $L_2$ have mutual coupling, $M$, which must be taken into account in determining the equivalent inductance for the resonant tank circuit. The frequency of oscillation is given approximately by

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

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

**Example:** Calculate the oscillator frequency for an FET Hartley oscillator of the following circuit values:

$C = 250 \text{ pF}$, $L_1 = L_2 = 2 \text{ mH}$, and $M = 0.5 \text{ mH}$.

**Solution:** Check $L_{eq} = 5 \text{ mH}$.

Check $f_o = 142.35 \text{ KHz}$.  

**Crystal Oscillator:**

A crystal oscillator is basically a tuned-circuit oscillator using a piezoelectric crystal as a resonant tank circuit. Crystal oscillators are used whenever great stability is required, such as communication transmitters and receivers.

**Piezoelectric effect of a quartz crystal:** a mechanical stress applied across the faces of the crystal, a difference of potential develops across opposite faces of the crystal. Similarly, a voltage applied across one set of faces of the crystal causes mechanical distortion in the crystal shape.

When alternating voltage is applied to a crystal, mechanical vibrations are set up—these vibrations having a natural resonant frequency dependent on the crystal.

The following Figure shows the crystal as represented by the equivalent electrical circuit.

The crystal as represented by the equivalent circuit can have 2 resonant frequencies. One resonant condition occurs when the reactances of the series RLC leg are equal (and opposite).

For this condition, *the series-resonant* impedance is very low ( = R). The other resonant condition occurs at a higher frequency when the reactance of the series-resonant leg equals the reactance of the capacitor $C_M$. This is a parallel resonance condition of the crystal. At this frequency, the crystal offers a very high impedance to the external circuit. The impedance versus frequency of the crystal is shown in the following Figure.
Series-Resonant Circuits

At the series-resonant frequency of the crystal, its impedance is smallest and the amount of (positive) FB is largest. A typical transistor circuit is shown in the following Figure.

Parallel-Resonant Circuits

Since the parallel-resonant impedance of a crystal is a maximum value, it is connected in shunt. At the parallel-resonant operating frequency, a crystal appears as an inductive reactance of largest value. The following Figure shows a crystal
connected as the inductor element in a modified Colpitts circuit. Maximum voltage is developed across the crystal at its parallel-resonant frequency. The voltage is coupled to the emitter by a capacitor voltage divider-capacitors $C_1$ and $C_2$.

**Crystal Oscillator**

An op-amp can be used in a crystal oscillator as shown in the following Figure. The crystal is connected in the series-resonant path and operates at the crystal series-resonant frequency. The circuit has a high gain so that an O/P square-wave signal results. A pair of Zener diodes is shown at the O/P to provide O/P voltage at exactly the Zener voltage ($V_z$).
Timer IC Unit Operation: (the 555 timer)

The IC is made of combination of linear comparators and digital Flip-Flops as described in the following Figure. A series connection of 3 resistors sets the reference voltage levels to the two comparators at 2Vcc/3 and Vcc/3, the O/P of these comparators setting or resetting the FF unit. The O/P of the FF circuit is then brought out thro' an O/P amplifier stage. The FF circuit also operates a transistor inside the IC, the transistor collector usually being driven low to discharge a timing capacitor.

Astable Operation: (astable multivibrator)
Capacitor C charges toward Vcc thro' external resistors $R_A$ and $R_B$. Referring to Figure, the capacitor voltage rises until it goes above $2Vcc/3$. This voltage is the threshold voltage at pin 6, which drives comparator 1 to trigger the FF so that the O/P at pin 3 goes low. In addition, the discharge transistor is driven on, causing the O/P at pin 7 to discharge the capacitor thro' resistor $R_B$. The capacitor voltage then decreases until it drops below the trigger level ($Vcc/3$). The FF is triggered so that the O/P goes back high and the discharge transistor is turned off, so that the capacitor can again charge thro' RA and RB toward Vcc.

Calculation of the time intervals during which the O/P is high and low can be made using the relations:

$$T_{\text{high}} \approx 0.7(R_A + R_B)C$$
$$T_{\text{low}} \approx 0.7R_B C$$

The total period is $T = \text{period} = T_H + T_L$.

The frequency of the astable circuit is then calculated using:

$$f = \frac{1}{T} \approx \frac{1.44}{(R_A + 2R_B)C}$$

The duty cycle "D"

$$D\% = \frac{T_{\text{high}}}{T} \times 100$$
Example: For the timer circuit shown in Figure:

a- Determine the frequency of the circuit.
b- Determine the duty cycle.
c- Draw the O/P waveform.

\[ T_{\text{high}} = 0.7(R_A + R_B)C = 0.7(7.5 \times 10^3 + 7.5 \times 10^3)(0.1 \times 10^{-6}) \]

\[ = 1.05 \text{ ms} \]

\[ T_{\text{low}} = 0.7R_B C = 0.7(7.5 \times 10^3)(0.1 \times 10^{-6}) = 0.525 \text{ ms} \]

\[ T = T_{\text{high}} + T_{\text{low}} = 1.05 \text{ ms} + 0.525 \text{ ms} = 1.575 \text{ ms} \]

\[ f = \frac{1}{T} = \frac{1}{1.575 \times 10^{-3}} \approx 635 \text{ Hz} \]

The duty cycle \( D\% = (1.05/1.575)\times100 = 67\% \)
Monostable Operation:

The 555 timer can be used as a one-shot or monostable multivibrator circuit, as shown in Figure. When the trigger I/P goes –ve, it triggers the one-shot, with O/P at pin 3 then going high for a time period.

\[ T_{\text{high}} = 1.1 \, R_A \, C \]

Referring to the Figure of the details of 555 timer, the –ve edge of the trigger i/p causes comparator 2 to trigger the FF, with the o/p at pin 3 going high. Capacitor C charges toward Vcc thro' resistor R_A. During the charge interval, the o/p remains high. When the capacitor voltage reaches the threshold level of \( 2Vcc/3 \), comparator 1 triggers the FF, with o/p going low. The discharge transistor also goes low, causing the capacitor to remain at near 0V until triggered again.

Figure (b) shows the i/p trigger signal and the resulting o/p waveform for the 555 one-shot timer. Time periods can range from microseconds to many seconds.
Example:

Determine the period of the o/p waveform for the circuit of the following Figure when triggered by a –ve pulse.

Applying equation:

\[ T_{\text{high}} = 1.1 \ R_A C \]

\[ = 1.1(7.5 \times 10^3)(0.1 \times 10^{-6}) \]

\[ = 0.825 \text{ ms} \]

Voltage-Controlled Oscillator:

A voltage-controlled oscillator (VCO) is a circuit that provides a varying o/p signal (typically square or triangular) whose frequency can be adjusted over a range controlled by dc voltage. An example of a VCO is the 566 IC shown in Figure.

The 566 IC contains current sources to charge and discharge an external capacitor C1 at a rate set by external resistor R1 and modulating dc i/p voltage. A Schmitt trigger circuit is used to switch the current sources between charging and discharging the capacitor, and the triangular voltage developed across the
capacitor and square wave from the Schmitt trigger are provided as o/ps thro' buffer amplifier.

The following Figure shows the pin connection of the 566 unit.

A free-running or center-operating frequency, $f_o$ can be calculated from:

$$f_o = \frac{2}{R_1C_1} \left( \frac{V^+ - V_c}{V^+} \right)$$

With the following practical circuit value restrictions:

a) $2 \ \text{KΩ} \leq R_1 \leq 20 \ \text{KΩ}$.

b) $(3/4)V^+ \leq V_c \leq V^+$

$V_c$ should be $< 1 \ \text{MHz}$.

d) $10 \ \text{V} \leq V^+ \leq 24 \ \text{V}$
**Example:** Determine the frequency of the following circuit.

\[ V_C = \frac{R_3}{R_2 + R_3} \quad V^+ = \frac{10 \, k\Omega}{1.5 \, k\Omega + 10 \, k\Omega} (12 \, V) = 10.4 \, V \]

\[ f_o = \frac{2}{(10 \times 10^3)(820 \times 10^{-12})}\left(\frac{12 - 10.4}{12}\right) \]

Check \( f_o = 32.52 \, \text{KHz} \)

**Example:** The following circuit shows how the o/p square-wave frequency can be adjusted using the i/p voltage, \( V_c \), to vary the signal frequency.

Potentiometer \( R_3 \) allows varying \( V_c \) from about 9 V to near 12 V, over the full 10:1 frequency range.

**a- R3 wiper at top**

\[ V_C = \frac{R_3 + R_4}{R_2 + R_3 + R_4} (V^+) \]

Check \( V_c = 11.74 \, V \), and \( f_o = 19.7 \, \text{KHz} \)

**b- R3 wiper at the bottom**

\[ V_C = \frac{R_4}{R_2 + R_3 + R_4} (V^+) \]

Check \( V_c = 9.19 \, V \), and \( f_o = 212.9 \, \text{KHz} \)