5.1 BASICS OF OSCILLATORS

CRITERIA FOR OSCILLATION

The canonical form of a feedback system is shown in Figure 5.1.1, and Equation 1 describes the performance of any feedback system (an amplifier with passive feedback Components constitute a feedback system).

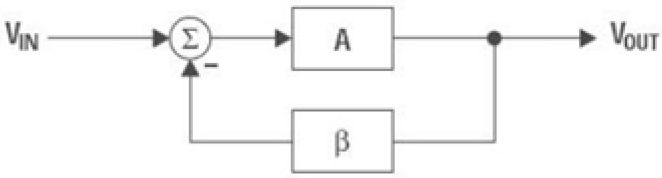

Figure 5.1.1 Canonical form of feedback circuit

[source: https://www.brainkart.com/subject/Linear-Integrated-Circuits_220/]

$$\frac{V_{OUT}}{V_{IN}} = \frac{A}{1 + A\beta} \qquad (1)$$

Oscillation results from an unstable state; i.e., the feedback system can't find a stable state because its transfer function can't be satisfied. Equation 1 becomes unstable when $(1+A\beta) = 0$ because A/0 is an undefined state. Thus, the key to designing an oscillator is to insure that $A\beta = -1$ (called the Barkhausen criterion), or using complex math the equivalent expression is $A\beta = 1\ -180°$. The 180° phase shift criterion applies to negative feedback systems, and 0° phase shift applies to positive feedback systems.

The output voltage of a feedback system heads for infinite voltage when $A\beta = -1$. When the output voltage approaches either power rail, the active devices in the amplifiers change gain, causing the value of A to change so the value of $A\beta \neq 1$; thus, the charge to infinite voltage slows down and eventually halts. At this point one of three things can occur.

First, nonlinearity in saturation or cutoff can cause the system to become stable and lock up.Second, the initial charge can cause the system to saturate (or cut off) and stay that way for a long time before it becomes linear and heads for the opposite power rail.
Third, the system stays linear and reverses direction, heading for the opposite power rail. Alternative two produces highly distorted oscillations (usually quasi square waves), and the

resulting oscillators are called relaxation oscillators. Alternative three produces sine wave oscillators.

PHASE SHIFT IN OSCILLATORS

The 180° phase shift in the equation Aβ = 1–180° is introduced by active and passive components. The phase shift contributed by active components is minimized because it varies with temperature, has a wide initial tolerance, and is device dependent. Figure 5.1.2 Shown below is the Phase plot of RC sections.

Amplifiers are selected such that they contribute little or no phase shift at the oscillation frequency. A single pole RL or RC circuit contributes up to 90° phase shift per pole, and because 180° is required for oscillation, at least two poles must be used in oscillator design.

An LC circuit has two poles; thus, it contributes up to 180° phase shift per pole pair, but LC and LR oscillators are not considered here because low frequency inductors are expensive, heavy, bulky, and non-ideal. LC oscillators are designed in high frequency applications beyond the frequency range of voltage feedback op amps, where the inductor size, weight, and cost are less significant.

Multiple RC sections are used in low-frequency oscillator design in lieu of inductors. Phase shift determines the oscillation frequency because the circuit oscillates at the frequency that accumulates –180° phase shift. The rate of change of phase with frequency, dS/dt, determines frequency stability.

When buffered RC sections (an op amp buffer provides high input and low output impedance) are cascaded, the phase shift multiplies by the number of sections, n (see Figure 2).Although two cascaded RC sections provide 180° phase shift, dS/dt at the oscillator frequency is low, thus oscillators made with two cascaded RC sections have poor frequency stability. Three equal cascaded RC filter sections have a higher dS/dt, and the resulting oscillator has improved frequency stability.

Adding a fourth RC section produces an oscillator with an excellent dS/dt, thus this is the most stable oscillator configuration. Four sections are the maximum number used

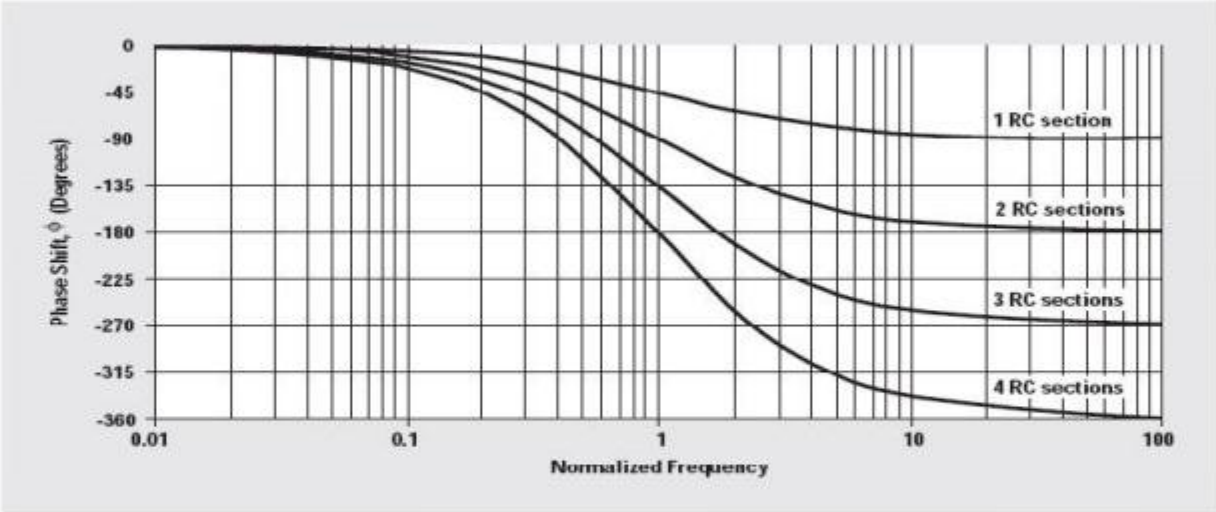

Figure 5.1.2 Phase plot of RC sections

[source: https://www.brainkart.com/subject/Linear-Integrated-Circuits_220/]

because op amps come in quad packages, and the four-section oscillator yields four sine waves that are 45° phase shifted relative to each other, so this oscillator can be used to obtain sine/cosine or quadrature sine waves.

APPLICATIONS

Crystal or ceramic resonators make the most stable oscillators because resonators have an extremely high dS/dt resulting from their non-linear properties. Resonators are used for high- frequency oscillators, but low-frequency oscillators do not use resonators because of size, weight, and cost restrictions.Op-amps are not used with crystal or ceramic resonator oscillators because op amps have low bandwidth. It is more cost-effective to build a high-frequency crystal oscillator and count down the output to obtain a low frequency than it is to use a low-frequency resonator.

GAIN IN OSCILLATORS

The oscillator gain must equal one (Aβ = 1–180°) at the oscillation frequency. The circuit becomes stable when the gain exceeds one and oscillations cease. When the gain exceeds one with a phase shift of –180°, the active device non-linearity reduces the gain to one.

The non-linearity happens when the amplifier swings close to either power rail because cutoff or saturation reduces the active device (transistor) gain. The paradox is that worst-case design practice requires nominal gains exceeding one for manufacturability, but excess gain causes more distortion of the output sine wave.

When the gain is too low, oscillations cease under worst-case conditions, and when the gain is too high, the output wave form looks more like a square wave than a sine wave.Distortion is a direct result of excess gain overdriving the amplifier; thus, gain must be carefully controlled in low distortion oscillators.Phase-shift oscillators have distortion, but they achieve low-distortion output voltages because cascaded RC sections act as distortion filters. Also, buffered phase-shift oscillators have low distortion because the gain is controlled and distributed among the buffers.

SINE WAVE GENERATORS (OSCILLATORS)

Sine wave oscillator circuits use phase shifting techniques that usually employ

- Two RC tuning networks, and
- Complex amplitude limiting circuitry

RC PHASE SHIFT OSCILLATOR

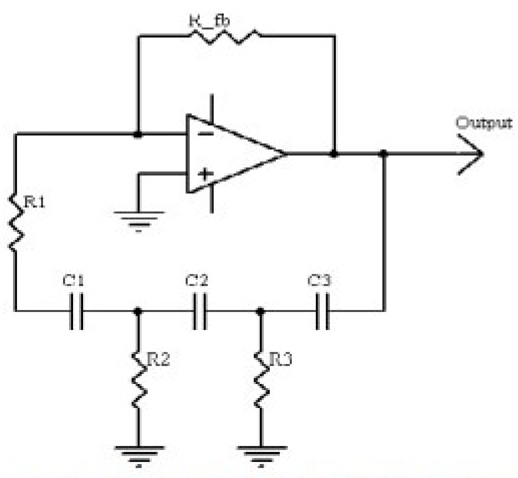

Figure 5.1.3 RC phase shift oscillator

[source: https://www.brainkart.com/subject/Linear-Integrated-Circuits_220/]

RC phase shift oscillator using op-amp in inverting amplifier introduces the phase shift of 180° between input and output. The feedback network consists of 3 RC sections each producing 60° phase shift. Such a RC phase shift oscillator using op-amp is shown in the figure 5.1.3.

The output of amplifier is given to feedback network. The output of feedback network drives the amplifier. The total phase shift around a loop is 180 of amplifier and 180 due to 3 RC sections, thus 360 º. This satisfies the required condition for positive feedback and circuit works as an oscillator.

$$f_{\text{oscillation}} = \frac{1}{2\pi\sqrt{R_2R_3(C_1C_2+C_1C_3+C_2C_3)+R_1R_3(C_1C_2+C_1C_3)+R_1R_2C_1C_2}}$$

Oscillation criterion:

$$R_{\text{feedback}} = 2(R_1+R_2+R_3)+\frac{2R_1R_3}{R_2}+\frac{C_2R_2+C_2R_3+C_3R_3}{C_1}$$

$$+\frac{2C_1R_1+C_1R_2+C_3R_3}{C_2}+\frac{2C_1R_1+2C_2R_1+C_1R_2+C_2R_2+C_2R_3}{C_3}$$

$$+\frac{C_1R_1^2+C_3R_1R_3}{C_2R_2}+\frac{C_2R_1R_3+C_1R_1^2}{C_3R_2}+\frac{C_1R_1^2+C_1R_1R_2+C_2R_1R_2}{C_3R_3}$$

$$A\beta = A\left(\frac{1}{RCs+1}\right)^3 \qquad (3)$$

The loop phase shift is –180° when the phase shift of each section is –60°, and this occurs when ω = 2πf = 1.732/RC because the tangent 60° = 1.73. The magnitude of β at this point is $(1/2)^3$, so the gain, A, must be equal to 8 for the system gain to be equal to 1.

WIEN BRIDGE OSCILLATOR

Figure 5.1.4 give the Wien-bridge circuit configuration. The loop is broken at the positive input, and the return signal is calculated in Equation 2 below.

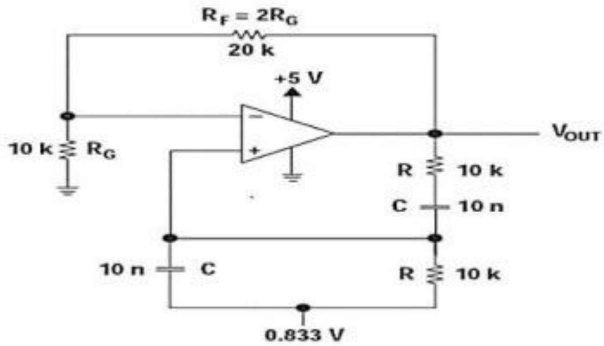

Figure 5.1.4 Wein Bridge oscillator

[source: https://www.brainkart.com/subject/Linear-Integrated-Circuits_220/]

$$\frac{V_{RETURN}}{V_{OUT}} = \frac{\frac{R}{RCs+1}}{\frac{R}{RCs+1} + R + \frac{1}{Cs}} = \frac{1}{3 + RCs + \frac{1}{RCs}} = \frac{1}{3 + j\left(RC\omega - \frac{1}{RC\omega}\right)}. \quad (2)$$

where $s = j\omega$ and $j = \sqrt{1}$.

When ω = 2πf = 1/RC, the feedback is in phase (this is positive feedback), and the gain is 1/3, so oscillation requires an amplifier with a gain of 3. When R_F = 2RG, the amplifier gain is 3 and oscillation occurs at f = 1/2πRC. The circuit oscillated at 1.65 kHz rather than 1.59 kHz with the component values shown in Figure 5.1.4 but the distortion is noticeable.

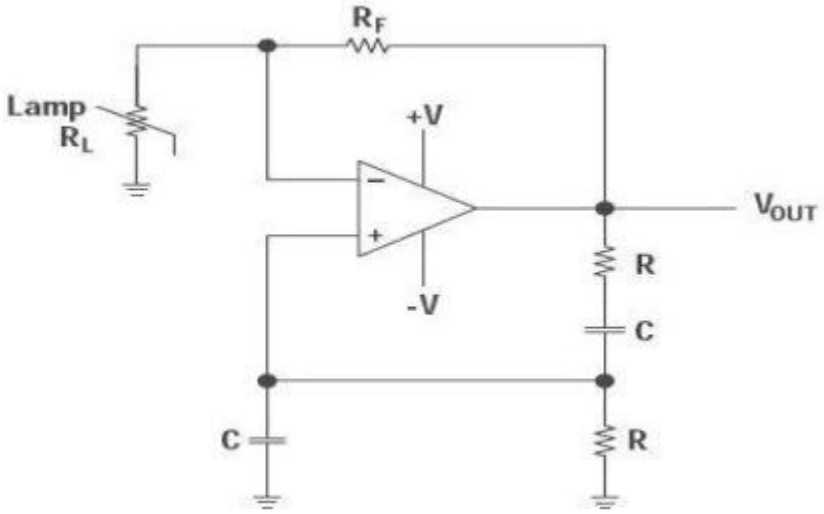

Figure 5.1.5 Wien-bridge circuit with non-linear feedback.

[source: https://www.brainkart.com/subject/Linear-Integrated-Circuits_220/]

Figure 5.1.5 shows a Wien-bridge circuit with non-linear feedback. The lamp resistance, R_L, is nominally selected as half the feedback resistance, R_F, at the lamp current established by R_F and R_L. The non-linear relationship between the lamp current and resistance keeps output voltage changes small.

If a voltage source is applied directly to the input of an **ideal** amplifier with feedback, the input current will be:

$$i_{in} = \frac{v_{in} - v_{out}}{Z_f}$$

Where *vin* is the input voltage, v_{out} is the output voltage, and Z_f is the feedback impedance. If the voltage gain of the amplifier is defined as:

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

And the input admittance is defined as:

$$Y_i = \frac{i_{in}}{v_{in}}$$

Input admittance can be rewritten as:

$$Y_i = \frac{1 - A_v}{Z_f}$$

For the Wien Bridge, *Zf* is given by:

$$Z_f = R + \frac{1}{j\omega C}$$

$$Y_i = \frac{(1 - A_v)\left(\omega^2 C^2 R + j\omega C\right)}{1 + (\omega C R)^2}$$

If *Av* is greater than 1, the input admittance is a negative resistance in parallel with an inductance.

The inductance is:

$$L_{in} = \frac{\omega^2 C^2 R^2 + 1}{\omega^2 C\,(A_v - 1)}$$

If a capacitor with the same value of *C* is placed in parallel with the input, the circuit has a natural resonance at:

$$\omega = \frac{1}{\sqrt{L_{in} C}}$$

Substituting and solving for inductance yields:

$$L_{in} = \frac{R^2 C}{A_v - 2}$$

If *Av* is chosen to be 3: $Lin = R^2C$

Substituting this value yields:

$$\omega = \frac{1}{RC} \quad \text{Or} \quad f = \frac{1}{2\pi RC}$$

Similarly, the input resistance at the frequency above is:

$$R_{in} = \frac{-2R}{A_v - 1}$$

For $A_v = 3$: $R_{in} = -R$

If a resistor is placed in parallel with the amplifier input, it will cancel some of the negative resistance. If the net resistance is negative, amplitude will grow until clipping occurs.Similarly, if the net resistance is positive, oscillation amplitude will decay. If a resistance is added in parallel with exactly the value of R, the net resistance will be infinite and the circuit can sustain stable oscillation at any amplitude allowed by the amplifier.

Increasing the gain makes the net resistance more negative, which increases amplitude. If gain is reduced to exactly 3 when suitable amplitude is reached, stable, low distortion oscillations will result.Amplitude stabilization circuits typically increase gain until suitable output amplitude is reached. As long as R, C, and the amplifier are linear, distortion will be minimal.