

Lecture 40: Different types of oscillators

Oscillators

DI02011011: Electronics Circuit and Application (ECA)

Agenda: Different Types of Oscillators

- Classification Framework: Waveform Type, Resonator Network, and Frequency Spectrum
- RC Audio Oscillators: 3-Stage RC Phase-Shift Topology
- RC Audio Oscillators: Wien-Bridge Lead-Lag Topology
- LC RF Oscillators: Hartley Tapped-Inductor Topology
- LC RF Oscillators: Colpitts Split-Capacitor Topology
- LC RF Oscillators: Clapp High-Stability Variant
- Crystal Oscillators: Quartz Resonator & Pierce Architecture
- Non-Sinusoidal Relaxation Oscillators & IC 555 Astable Circuits
- Voltage-Controlled Oscillators (VCO) & Phase-Locked Loops (PLL)
- Comparative Analysis Matrix across all Oscillator Families
- Summary & Engineering Selection Guide

Classification Framework for Electronic Oscillators

- Classification by Output Waveform: Sinusoidal (Harmonic) Oscillators produce pure sine waves; Non-Sinusoidal (Relaxation) Oscillators produce square, pulse, or triangular waveforms.
- Classification by Frequency Network: RC Networks (10 Hz – 1 MHz); LC Tanks (100 kHz – 500 MHz); Piezoelectric Crystals (32.768 kHz – 200 MHz); Cavity Resonators (> 1 GHz).
- Classification by Frequency Spectrum: Audio Frequency (AF: 20 Hz – 20 kHz); Radio Frequency (RF: 100 kHz – 300 MHz); Very High Frequency (VHF/UHF: 30 MHz – 3 GHz); Microwave (> 3 GHz).
- Classification by Excitation Mode: Self-excited (feedback oscillators) vs Negative resistance (Gunn/Tunnel diode oscillators).

RC Audio Oscillators: 3-Stage RC Phase-Shift Topology

- Circuit Topology: Inverting amplifier (Op-Amp or CE BJT, 180° phase shift) cascaded with 3-stage high-pass RC ladder feedback network (180° phase shift).
- Resonant Frequency Formula: $f_0 = \frac{1}{2\pi RC\sqrt{6}}$ for equal R, C ladder stages.
- Feedback Factor & Gain Criterion: Feedback factor $\beta(j\omega_0) = -\frac{1}{29}$. To satisfy Barkhausen criterion $A\beta = 1$, inverting amplifier gain must be $|A_v| \geq 29$.
- Engineering Pros & Cons: Pro: Does not require bulky inductors, ideal for fixed audio frequencies (10 Hz – 100 kHz). Con: Poor frequency tuning flexibility since changing f_0 requires ganging 3 variable capacitors.

RC Audio Oscillators: Wien-Bridge Lead-Lag Topology

- Circuit Topology: Non-inverting Op-Amp stage (0° phase shift) paired with series-parallel RC bridge feedback network.
- Resonant Frequency Formula: $f_0 = \frac{1}{2\pi RC}$.
- Feedback Factor & Gain Criterion: At $\omega_0 = \frac{1}{RC}$, phase shift is zero and feedback factor $\beta(j\omega_0) = \frac{1}{3} \angle 0^\circ$. Requires non-inverting amplifier gain $A_v = 1 + \frac{R_f}{R_1} = 3$ ($\frac{R_f}{R_1} = 2$).
- Features & Applications: Excellent frequency tuning across 10 Hz – 1 MHz using dual-ganged variable resistors/capacitors; extremely low total harmonic distortion (THD < 0.1%) when stabilized with JFET AGC or thermistor.

LC RF Oscillators: Hartley Tapped-Inductor Topology

- Circuit Topology: Transistor amplifier combined with LC tank consisting of tapped inductor (L_1, L_2) and single tuning capacitor C .
- Resonant Frequency Formula: $f_0 = \frac{1}{2\pi\sqrt{L_T C}}$, where equivalent total inductance is $L_T = L_1 + L_2 + 2M$ (M is mutual inductance).
- Feedback Factor & Gain Criterion: Feedback ratio $\beta = \frac{L_1+M}{L_2+M}$; required amplifier voltage gain $|A_v| \geq \frac{L_2+M}{L_1+M}$.
- Applications & Limitations: Easily tuned across RF band (100 kHz – 30 MHz) using single variable capacitor C . Main disadvantage: Mutual inductance variations between coil taps cause frequency instability.

LC RF Oscillators: Colpitts Split-Capacitor Topology

- Circuit Topology: Active amplifier coupled with tank circuit using split capacitive voltage divider (C_1, C_2) and single inductor L .
- Resonant Frequency Formula: $f_0 = \frac{1}{2\pi\sqrt{LC_{eq}}}$, where $C_{eq} = \frac{C_1 C_2}{C_1 + C_2}$.
- Feedback Factor & Gain Criterion: Feedback ratio $\beta = \frac{C_1}{C_2}$; required amplifier voltage gain $|A_v| \geq \frac{C_1}{C_2}$.
- Superior Stability: Eliminates mutual inductance problems of Hartley oscillator; provides excellent high-frequency performance in RF/VHF range (1 MHz – 300 MHz).

LC RF Oscillators: Clapp High-Stability Variant

- Circuit Enhancement: Advanced derivative of Colpitts oscillator incorporating a small variable tuning capacitor $C_3 \ll C_1, C_2$ in series with tank inductor L .
- Equivalent Capacitance Derivation: $C'_{eq} = \frac{1}{\frac{1}{C_1} + \frac{1}{C_2} + \frac{1}{C_3}} \approx C_3$ (since $C_3 \ll C_1, C_2$).
- Resonant Frequency Formula: $f_0 \approx \frac{1}{2\pi\sqrt{LC_3}}$.
- Transistor Parasitic Immunity: Transistor junction capacitances C_{in}, C_{out} appear in parallel with large capacitors C_1, C_2 . Because $C_3 \ll C_1, C_2$, thermal variations in transistor capacitances have negligible impact on f_0 , providing outstanding frequency stability.

Crystal Oscillators: Quartz Resonator & Pierce Architecture

- Piezoelectric Mechanism: Piezoelectric AT-cut quartz crystal wafer converts mechanical acoustic resonance into electrical oscillations.
- Pierce Oscillator Topology: Quartz crystal operates in inductive region between series load capacitors C_1 , C_2 , connected across CMOS inverter or BJT amplifier.
- Resonant Frequency Stability: Frequency drift is less than $\pm 1 - 10$ ppm over temperature, backed by crystal quality factor $Q \sim 100,000$.
- Ubiquitous Applications: Digital system clocking (32.768 kHz watch crystals, 12 MHz microcontrollers, 25 MHz Ethernet PHYs, 100 MHz PCIe clocks).

Relaxation Oscillators & IC 555 Astable Circuits

- Operating Principle: Non-sinusoidal periodic signal generation through dynamic charging and discharging of timing capacitor C between threshold voltages.
- IC 555 Astable Multivibrator Topology: Capacitor C charges through $(R_A + R_B)$ to $\frac{2}{3}V_{CC}$ and discharges through R_B to $\frac{1}{3}V_{CC}$.
- Timing & Frequency Equations: Charge time $t_H = 0.693(R_A + R_B)C$; Discharge time $t_L = 0.693R_B C$; Total Period $T = 0.693(R_A + 2R_B)C$; Frequency $f = \frac{1.44}{(R_A + 2R_B)C}$.
- Duty Cycle Formulation: $D = \frac{t_H}{T} = \frac{R_A + R_B}{R_A + 2R_B}$ (always $> 50\%$ for standard configuration).

Voltage-Controlled Oscillators (VCO) & Synthesizers

- VCO Core Architecture: LC tank or ring oscillator where effective tuning capacitance is varied by an external control voltage V_{ctrl} using varactor diodes.
- VCO Transfer Characteristic: Linearized output frequency equation $f_o = f_c + K_{VCO} \cdot V_{ctrl}$, where K_{VCO} is VCO gain constant in MHz/V.
- Ring Oscillator VCO: Chain of an odd number N of CMOS inverters; frequency $f_o = \frac{1}{2Nt_{pd}(V_{ctrl})}$, tuned by controlling inverter supply current.
- Phase-Locked Loop (PLL) Integration: VCO is locked to a stable crystal reference oscillator inside PLL frequency synthesizers for FM modulation and clock multiplication.

Comparative Oscillator Performance Matrix

- RC Phase-Shift: Frequency Range 10 Hz – 100 kHz — Formula $f_0 = \frac{1}{2\pi RC\sqrt{6}}$ — Medium Stability — Uses Inverting Gain $|A_v| \geq 29$ — Audio Fixed Signals.
- Wien-Bridge: Frequency Range 10 Hz – 1 MHz — Formula $f_0 = \frac{1}{2\pi RC}$ — High Stability (Low THD) — Uses Non-inverting Gain $A_v = 3$ — Precision Audio Generators.
- Hartley: Frequency Range 100 kHz – 30 MHz — Formula $f_0 = \frac{1}{2\pi\sqrt{L_T C}}$ — Fair Stability — Tapped Inductor $\beta = \frac{L_1+M}{L_2+M}$ — RF Transmitters.
- Colpitts: Frequency Range 1 MHz – 300 MHz — Formula $f_0 = \frac{1}{2\pi\sqrt{L C_{eq}}}$ — Good Stability — Split Capacitor $\beta = \frac{C_1}{C_2}$ — VHF/RF Receivers.
- Clapp: Frequency Range 10 MHz – 500 MHz — Formula $f_0 \approx \frac{1}{2\pi\sqrt{L C_3}}$ — Excellent Stability — Series Capacitor $C_3 \ll C_1, C_2$ — High-Stability RF local oscillators.
- Pierce Crystal: Frequency Range 32 kHz – 200 MHz — Formula $f_0 = f_s$ or f_p — Ultra-High (± 1 ppm) — Quartz Resonator ($Q \sim 10^5$) — Microcontroller / Digital Clocks.

Summary: Key Takeaways on Oscillator Types

- RC Oscillators: Phase-Shift ($f_0 = \frac{1}{2\pi RC\sqrt{6}}$, $A_v = 29$) and Wien-Bridge ($f_0 = \frac{1}{2\pi RC}$, $A_v = 3$) for audio frequency generation.
- LC Oscillators: Hartley (tapped coil), Colpitts (split capacitor), and Clapp (series capacitor C_3) for radio frequency and VHF applications.
- Crystal Oscillators: Quartz crystal resonators ($Q \sim 100,000$) deliver $\pm 1 - 10$ ppm frequency stability in Pierce configurations.
- Relaxation & VCO Systems: IC 555 astable multivibrators generate square waves ($f = \frac{1.44}{(R_A + 2R_B)C}$), while VCOs enable electronic frequency synthesis in PLLs.