

Phase Noise in Oscillators

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As well known from oscillator theory, two conditions are required to make a feedback system oscillate: the open loop gain must be greater than unity; and total phase shift must be 360 degrees at the frequency of oscillation.

An oscillator circuit can be a combination of an amplifier with gain $A(j\omega)$ and a frequency dependent feedback loop $H(j\omega) = \beta A$. Oscillator has positive feedback loop at selected frequency.

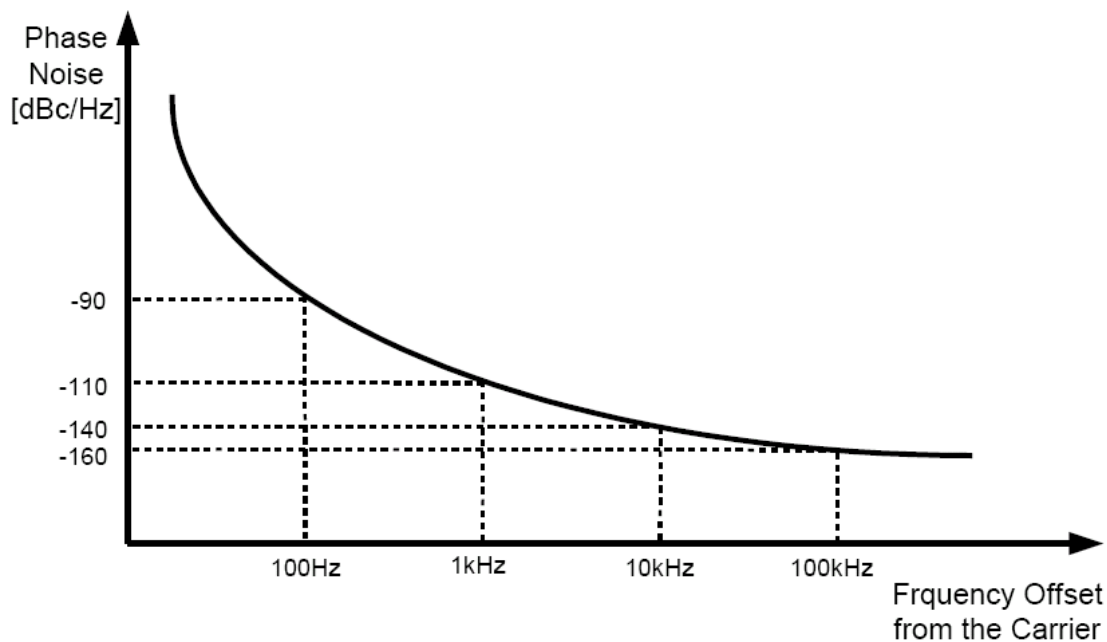
- Frequency stability is a measure of the degree to which an oscillator maintains the same value of frequency over a given time.
- Phase Noise can be described as short-term random frequency fluctuations of a signal; is measured in the frequency domain, and is expressed as a ratio of signal power to noise power measured in a 1 Hz bandwidth at a given offset from the desired signal.
- Low oscillator Phase Noise is a necessity for many receiving and transmitter systems. Adjacent channel rejection as well as transmitter signal purity are dependent on the Phase Noise of the receiver local oscillator or transmit local oscillator.
- The local oscillator Phase Noise will limit the ultimate Signal-to-Noise ratio (SNR) which can be achieved when listening to a frequency modulated (FM) or phase-modulated (PM) signal.
- The oscillator Phase Noise is transferred to the carrier to which the receiver is tuned and is then demodulated by the FM discriminator. The Phase Noise results in a constant noise power output from the discriminator.
- The performance of some types of AM detectors or SSB detectors may be degraded by the local oscillator Phase Noise. Reciprocal mixing may cause the receiver noise floor to increase when strong signals are near the receiver's tuned frequency; this limits the ability to recover weak signals. All of these effects are due to local oscillator Phase Noise, and can only be reduced by decreasing the Phase Noise.
- Local oscillator Phase Noise will affect the Bit Error Rate (BER) performance of a Phase-Shift Keyed (PSK) digital transmission system. A transmission error will occur any time if the local oscillator phase, due to its noise, becomes sufficiently large that the digital phase detection makes an incorrect decision as to the transmission phase. For instance, a QPSK transmission system (used in Microwave Links, CDMA, DVB, etc) will make a transmission error if the instantaneous oscillator phase is offset by more than 45° since the phase detector will determine that baud to be in the incorrect quadrant. Digital transmission systems with smaller phase multiples are more sensitive to degradation due to local oscillator Phase Noise.

A Variable Controlled Oscillator (VCO) part of a Phase-Locked Loop (PLL), will always have some spurious signals present on its output. The amplitude and frequency of these spurious modulations may vary as the local oscillator is tuned.

- Poor layout of the phase-locked loop oscillator circuitry may increase the amplitude and number of these spurious signals.
- Oscillator Phase Noise has two components: Phase Noise resulting from direct upconversion of white noise and flicker noise (1/f noise), and Phase Noise resulting from the changing phase of the noise sources modulating the oscillation frequency.

The Phase Noise of an oscillator is best described in the frequency domain where the spectral density is characterized by measuring the noise sidebands on either side of the output signal center frequency.

- Single Side Band (SSB) Phase Noise is specified in dBc/Hz at a given frequency offset from the carrier.



SSB Phase Noise places limit on receiver Adjacent Channel Selectivity (ACS) and also affects the receiver Signal to Noise Ratio.

A model for oscillator SSB Phase Noise was introduced by [David B. Leeson](#) in 1966.

$$\mathcal{L}_{PM} \approx 10 \log \left[\frac{FkT}{A} \frac{1}{8Q_L^2} \left(\frac{f_0}{f_m} \right)^2 \right]$$

\mathcal{L}_{PM} = Single Side Band (SSB) Phase Noise density [dBc/Hz]

A = Oscillator output power [W]

F = device Noise Factor at operating power level A (linear)

k = Boltzmann's constant, 1.38×10^{-23} [J/K]

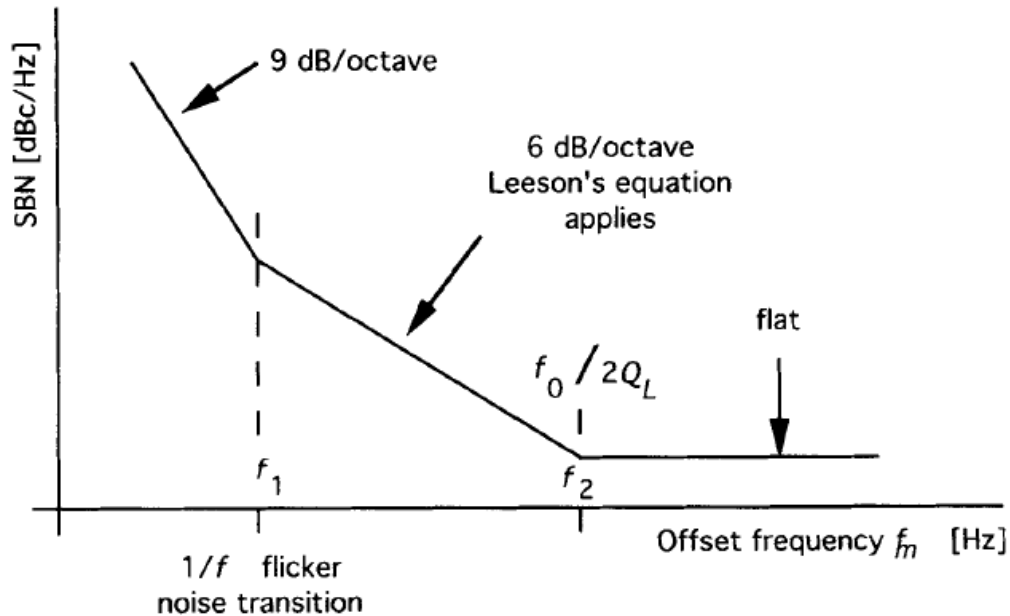
T = Temperature [K]

Q_L = Loaded-Q [dimensionless]

f_o = Oscillator carrier frequency [Hz]

f_m = Frequency offset from the carrier [Hz]

Leeson's equation only applies between $1/f$ flicker noise transition frequency (f_1) and a frequency (f_2) where white noise (flat) dominates.

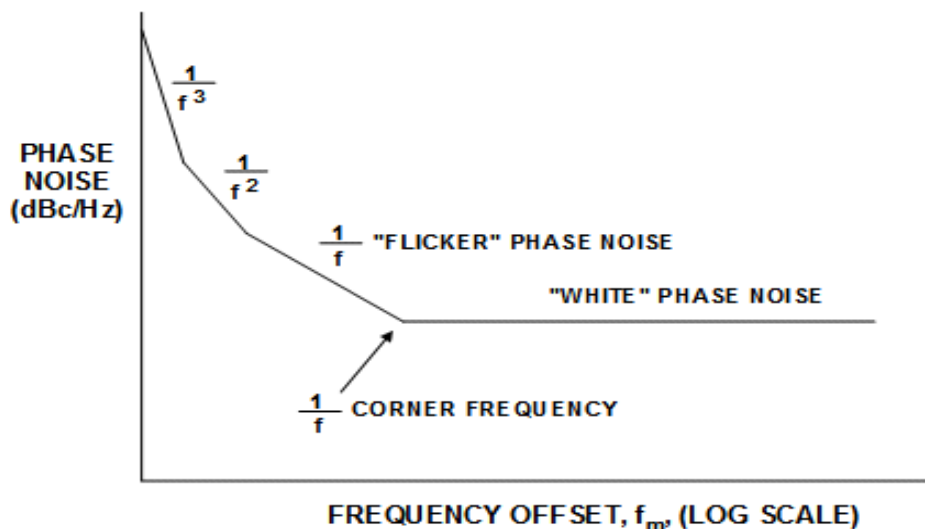


Leeson equation provides several insights about oscillator SSB Phase noise:

- Doubling the Loaded-Q improves Phase Noise by 6dB
- Doubling the operation frequency results 6dB Phase Noise degradation.

Unloaded-Q means the resonant circuit is not loaded by any external terminating impedance. In this case the Q is determined only by resonator losses.

Loaded-Q means the width of the resonance curve, or phase slope, including the effects of external components. In this case the Q is determined mostly by the external components.



- In the figure above Phase Noise in dBc/Hz is plotted as a function of frequency offset (f_m), with the frequency axis on a log scale. Note that the actual curve is approximated by a number of regions, each having a slope of $1/f^x$, where $x = 0$ corresponds to the "white" phase noise region (slope = 0 dB/decade), and $x = 1$ corresponds to the "flicker $1/f$ " phase noise region (slope = 20 dB/decade). There are also regions where $x = 2, 3, 4$, and these regions occur progressively closer to the carrier frequency.

Whilst harmonics can be filtered out by a simple low pass-filter, the spurious levels close to the wanted signal can only be minimized by careful oscillator design:

- Power Supply (V_{cc}) and tuning voltage (V_{tune}) returns must be connected to the printed circuit board ground plane. VCO ground plane must be the same as that of the printed circuit board and therefore all VCO ground pins must be soldered direct to the printed circuit board ground plane.
- Adequate RF grounding is required. Several chip decoupling capacitors must be provided between the V_{cc} supply and ground.
- Good, low noise power supplies must be used to prevent AM noise. Ideally, DC batteries for both supply (V_{CC}) and tuning (V_{tune}) voltages will provide the best overall performance.
- Output must be correctly terminated with good load impedance. It is also a good practice to use a resistive pad between the VCO and the external load.
- Connections to the tuning port must be as short as possible and must be well screened, shielded, and decoupled to prevent the VCO from being modulated by external noise sources. A low noise power supply must be used for tuning voltage (V_{tune}) Supply.
- Avoid saturation of the active devices at all cost, and try to have either limiting or automatic gain control (AGC) without degradation of the Q of the resonator.
- Using active components with low $1/f$ -noise. Flicker noise in BJTs is also known as $1/f$ noise because of the $1/f$ slope characteristics of the noise spectrum (the amplitude varies inversely with frequency). Mainly traps associated with contamination and crystal defects in the emitter-base depletion layer cause this noise. These traps capture and release carriers in a random fashion. The time constants associated with the process produce a noise signal at low frequencies.

In order to design an oscillator with low $1/f$ noise, the following are required:

- A resonating circuit (Crystal, L, C or Varactor) with a high Q-factor
- Active components with low flicker noise or $1/f$ -noise

To construct a resonant structure with a high Q-factor low losses are required in all of the constituent parts.

The following points should therefore be carefully considered:

- Q of resonator device itself
- Series resistance of capacitors
- Series resistance of tuning diode
- Loss of printed circuit board

Low $1/f$ noise of the transistor in the oscillator is very important, because the $1/f$ noise appears as sideband noise around the carrier frequency of the oscillator output signal.

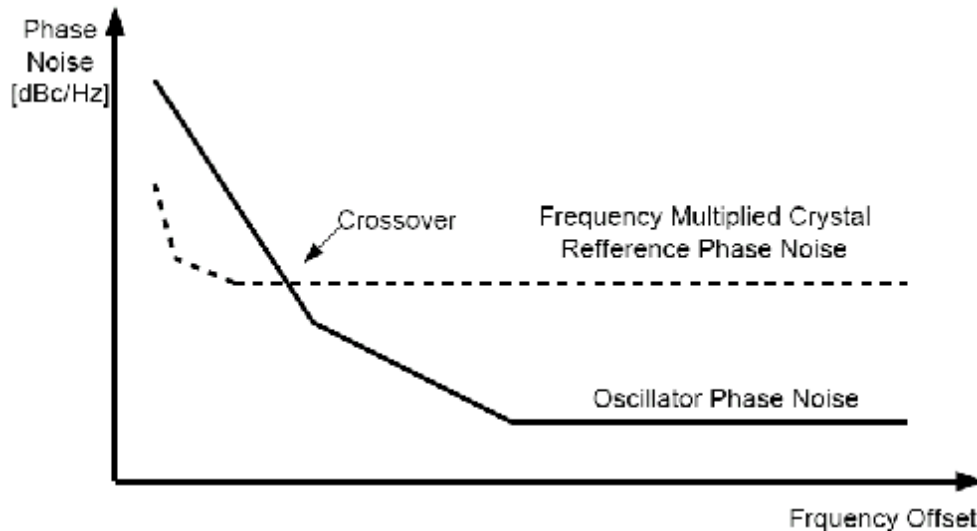
The basic rules to select the right transistor for an optimized design are:

- The best oscillator transistor is a device with the lowest possible noise figure and lowest f_T . A commonly used criteria is: $f_T \leq 2 * f_{osc}$.
- The $1/f$ noise is directly related to the current density in the transistor. Transistors with high I_{cmax} used at low currents have best $1/f$ performance. For low phase noise operation use a medium power transistor. If you need your output power to be achieved at 6-9 mA, select a transistor with I_{cmax} of 60-90 mA. However, the f_T of a transistor drops as current is decreased. Additionally, the parasitic capacitances of a high current transistor are higher due to the larger transistor structure required.
- The effect of flicker noise can be reduced through RF feedback. An unbypassed emitter resistor of 10-30 Ω in a BJT circuit can improve the flicker noise by as much as 40 dB. The proper bias point of the active device is important.
- Precautions should be taken to prevent modulation of the input and output dynamic capacitances of the active device; which will cause amplitude-to-phase conversion and therefore introduce noise.
- Low noise figure combined with a small correlation coefficient
- Higher output power
- Low output conductance
- Reasonably high input impedance
- Meeting an impedance condition at the input of the active device, which can be achieved by optimization of the feedback factor and which leads to optimum impedance noise matching.

In a PLL the design of the loop filter can affect the Phase Noise of the system:

- Within the loop bandwidth, the Phase Noise of the oscillator will tend to cancel itself, leaving a Phase Noise essentially equal to the frequency multiplied Phase Noise of the crystal reference.
- Multiplied Phase Noise of the crystal reference at particular frequency offset is equal with reference Phase Noise at the same frequency offset plus $20 * \text{LOG}(N_{VCO_divider})$ plus 1dB (multiplication efficiency factor)
- Outside the loop bandwidth, the Phase Noise of the oscillator is not canceled, and will continue to decrease, until reaching its half bandwidth, $\omega_o/2Q$ or $1/f$ corner frequency. Since the Q of the crystal reference is very large, its half bandwidth is very small, and its frequency multiplied Phase Noise will remain relatively flat down to very small frequency offsets. Further, at some moderate frequency offset, this multiplied phase noise power spectral-density will be crossed by the decreasing oscillator phase noise power spectral-density.

- The bandwidth of the loop should be chosen equal to the frequency offset of this crossover.
- Although the phase-locked loop bandwidth is not a barrier frequency with a discontinuity on either side of the barrier, it can be approximated as such with the proviso that small errors around the offset frequency equal to the loop bandwidth are accepted.



- The role of the loop filter, which is a low-pass filter inserted between the phase comparator and the VCO control voltage circuit, eliminates the high frequency component of the phase correction pulse generated by the phase comparator so that the only the DC component is provided to the VCO.
- As a rule of thumb, the cut off frequency of the low-pass filter is chosen as equal or less than comparison frequency divided by ten ($F_{\text{cutoff}} < F_{\text{comparison}} / 10$).
- Usually the low-pass filter is an RC network. The analysis of the Phase Noise performance shows that the Phase Noise depends on the resistor value, part of the low-pass filter. The higher the resistor, the higher is its contribution to the phase noise.

Continuing with parameters that affect VCO Phase Noise we can see:

- When frequency of the carrier increases, it is more difficult to achieve good Phase Noise
- It's easy to achieve good Phase Noise when the frequency range covered by VCO is narrow; the tuning bandwidth must be small. Generated energy should be coupled from the resonator rather than from another portion of the active device so that the resonator limits the bandwidth.
- Increasing tuning sensitivity (measured in MHz / V) degrades Phase Noise.
- For a given frequency it's easy to achieve good Phase Noise in VCO's using a wide tuning voltage range.
- Temperature affects the Phase Noise. In a range of -55°C to $+85^{\circ}\text{C}$ the variation is ± 3 dB of the Phase Noise.

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