An introduction to phase noise in VCOs.

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1.0 Introduction

Introduction. This analysis and documentation of VCO design with an associated expose of the critical phase noise (and also of other noise sources) is an attempt to see what can be achieved with readily available and stable silicon technonolgy. Since noise is so important it is advisable to first analyze this before launching into the VCO design proper. It is an integral part of the VCO design process.

2.0 Phase noise and associated parameters:

Phase noise is best described in the following way. If the short term stability of an oscillator is examined using a spectrum analyzer, it shows a spectrum consisting of random and discrete frequency components causing a broad skirt and spurious peaks This is shown in Figure 1 below. If the oscillator was noise free the spectrum would consist of a single spectral line. The broadening of the spectrum is caused by various noise sources including thermal noise, shot noise or flicker noise in active and passive devices. This broadening is due to the phenomenon of *phase noise.*

Typically phase noise is depicted as shown in Figure 1 with its associated parameters.

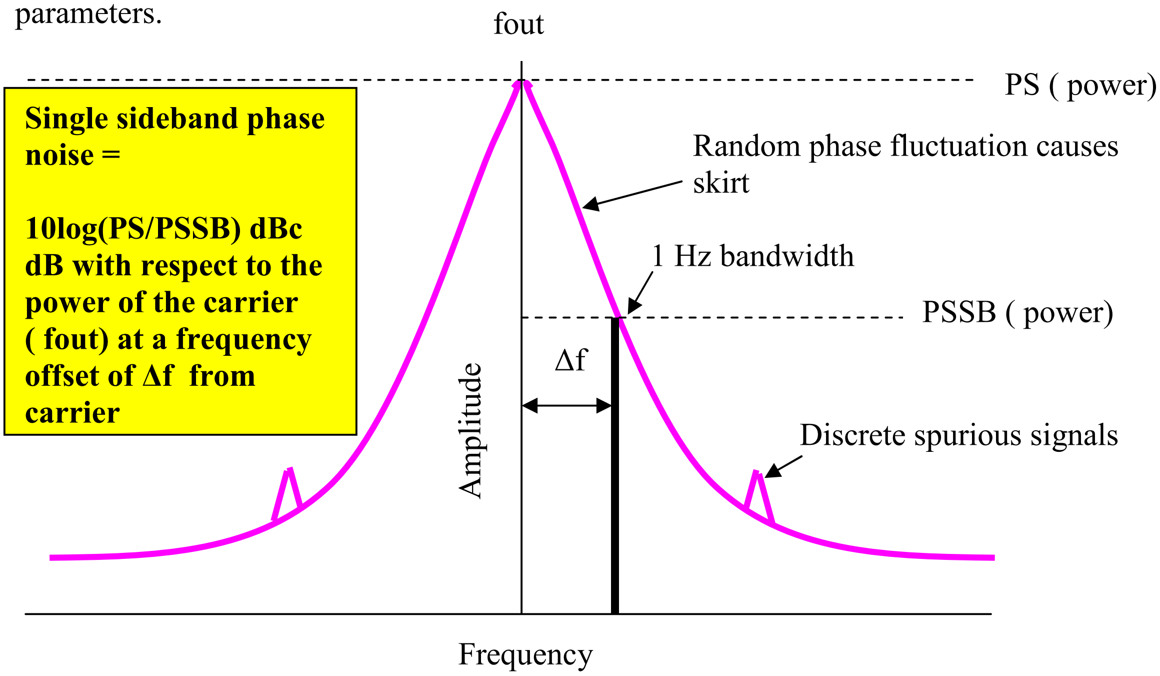


Figure 1.0 A double sideband representation of oscillator output.

It is also possible to convert the rms value of the phase noise into a phase error or jitter. This is expressed in rms picoseconds or rms degrees.

An early model for the phase noise spectrum of oscillators was formulated without proof by D.B Leeson and is shown below. Variations of this model now exist for the modeling of phase noise in oscillators.

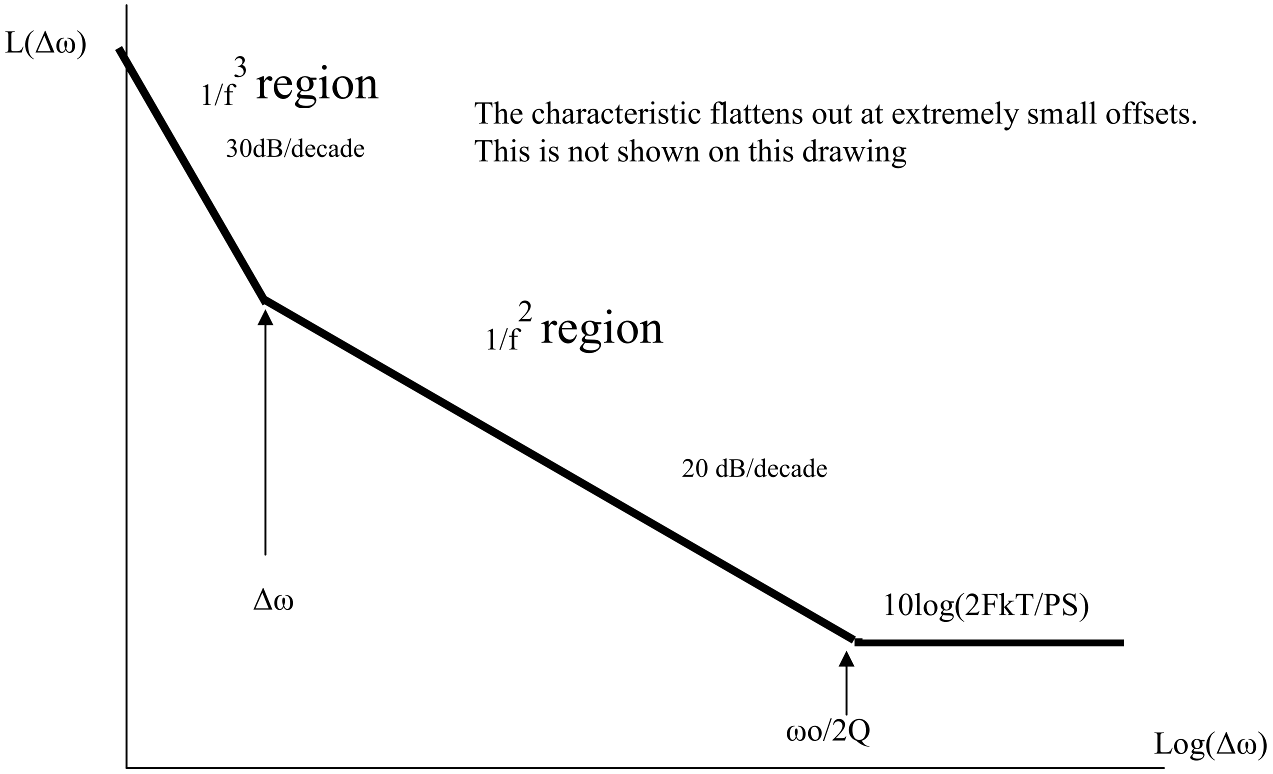
Leeson's model can be written as:

$$L(\Delta\omega) = 10 \log [(2FkT/PS)\{ 1+ (\omega o/2Q\, \Delta\omega)^2 \}(1 + \Delta\omega_{1/f^3} / |\Delta\omega|) \qquad (1)$$

Where the units for L are *decibels below the carrier per Hz* or *dBc/Hz*.

Here k = Boltzman's constant = 1.38 x 10^{-23} J/K
T = absolute temperature
F = a fitting factor depending on the particular circuit used.
PS = power of the carrier
Q = loaded quality factor of the circuit
$\Delta\omega$ frequency offset from the carrier (Hz)
ωo = carrier frequency (Hz)

The graphical representation of this model is shown in Figure 2.0



The characteristic flattens out at extremely small offsets. This is not shown on this drawing

Figure 2. Phase noise characteristic: Leeson's equation

2.1 Buffer amplifier noise:

The use of a buffer amplifier is sometimes unavoidable in some applications. When this is the case the noise of the buffer amplifier should be included in the overall analysis. The buffer degrades phase noise performance if its thermal noise, referenced to the input, exceeds the oscillator output phase noise at a given offset frequency. The buffer amplifier thermal noise floor referenced to the input in a 1 Hz BW is:

Ni = FkT (watts/hertz) , F = Amplifier thermal noise factor.

2.2 Varactor modulation phase noise:

A LC oscillator is tuned using an on chip varactor (junction or gate type). Any noise voltage(or current) impressed on this device will cause FM modulation of the VCO. This is also referred to as varactor modulation noise.

The equivalent noise voltage modulating the varactor is given by:

Vn = sqrt(4KTRvar) v/root Hz. (2)

Here Rvar is the *effective noise resistance* of the varactor. This quantity needs to be determined empirically if not specified in the process parameters provided by the fabrication vendor.

The equation above assumes a noiseless modulation source. If the source has a high resistance then the total noise is the square root of the sum – of – the squares of the two noise voltages.

The resultant phase noise is: (Single Sideband)

L(fm) = 20(logTHETAd)/2 (3)

THETAd = [sqrt(2)KvcoVn]/2fm (4)

Where fm = carrier offset frequency in hertz.
Kvco = VCO gain constant

The total phase noise will be that calculated from Leeson and the varactor noise above (power sum).

2.3 Power supply noise:

Power supply noise can arise from a variety of sources. Bipolar regulators, Zeners etc all generate noise superimposed on the DC output voltage.

2.4 Current source noise:

Typically a LC VCO is based on a differential pair plus a current sink (or tail current). Any noise in the tail current will be frequency translated by the switching of the differential transistors (analogous to a single balanced mixer). The low frequency noise of the current source gets mixed upwards in frequency to appear as a pair of sidebands around the carrier and injected into the tuned LC circuit.

2.5 Noise in the differential pair:

Noise in the differential pair is injected into the tuned LC circuit when the differential pair is operating in its active region. Current noise pulses appear at the differential pair output.

2.6 LC tuned circuit noise:

The LC tuned circuit has a loss depending on its loss resistance. This causes a noise component. The differential stage picks up this noise component and presents it at the output. Increasing the Q of the LC circuit improves this noise performance.

2.7 Thermal noise:

Needless to say, any number of thermal noise sources exist in the VCO ciruit and all have to be taken into account (or to be practical, simulated). Thermal noise plays a major role at high offset frequencies.

Some of these noise sources can be simulated using industry standard simulators while others are more of an engineering judgement issue (which cannot directly be simulated).

All these noise sources will affect the phase noise of the VCO, and ultimately define the performance of the system the VCO is used in.

A useful identity to use in these cases is the Leeson Identity with suitable modifications.

2.8 Flicker noise:

The design engineer also needs to be aware of flicker noise. The phase noise curve changes to a 20dB curve near the carrier.

2.9 Jitter:

Brief mention must be made about *jitter*, the time domain guise of phase noise

(and vice versa). The duality of phase noise and jitter means that one can be converted into the other. The conversion can be done as follows:

Using the SSB phase noise plot, calculate the noise power from any frequency f1 to f2. This is done by calculating the area under the plot for these end points. This yields N, the noise power.(A number of rules for integration are available in the literature to do this (Trapezoidal, Simpson's etc).

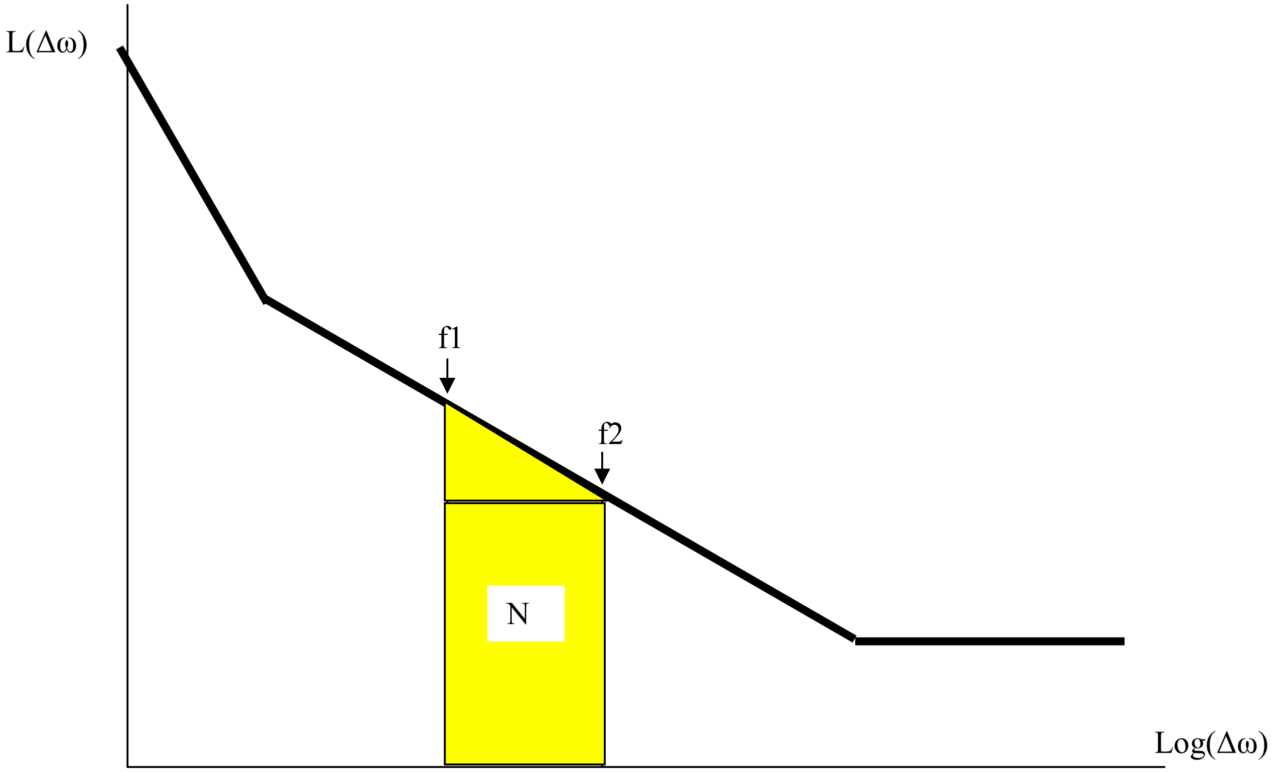


Figure 3. Calculating phase noise from f1 to f2

Once the noise power is found, the jitter can be estimated from:

Phase jitter in radians:

$$\mathrm{Sqrt}[(10^{N/10})] * 2.0 \tag{5.0}$$

Or phase jitter in time units:

Rms jitter in sec = jitter (radians)/(2πfosc)

where fosc = the center frequency of the oscillator.

3.0 **Conclusions**

: The design of VCOs is an art, in spite of a number of CAD tools that have come into existence recently. It will remain so in the forseeable future. An understanding of the noise sources which influence VCO design (or any oscillator design) can only benefit the designer. That is what this brief paper is about. We sincerely hope that the reader will find it to be of use in design practice.