APPLICATION NOTE - Jitter and Phase Noise

An Introduction to Noise and Jitter

A measurement of the performance of a frequency system is its stability, i.e. the level of fluctuations in frequency over a suitable measurement. The goal is to keep these fluctuations to a minimum; however noise and jitter are unavoidable within a system and can negatively affect the performance.

Jitter: A Basic Introduction

Consider a signal that has two states, 'on' or 'off'. This signal has a constant time period between the pulses and all the pulses are equal in length.

Due to the predictable nature of the signal, it is easy to anticipate when the next pulse will arrive. If desired, you could set up a system that utilises the characteristics of this pulse. For instance, if the time between two pulses were a multiple of a second, you could create a straightforward timing device based on this signal.

However, in reality, nothing is this simple. Consider again the signal, but now also consider something corrupting it. This 'noise', be it from within the pulse or an external parameter, occasionally causes the pulse to arrive either earlier or later than when it was supposed to.

This is essentially jitter and can be quite problematic by causing timing degradation.

Noise Basics

Noise refers to any unwanted information within a signal, from internal or external sources. Some noise is unavoidable, while others can be removed from the system.

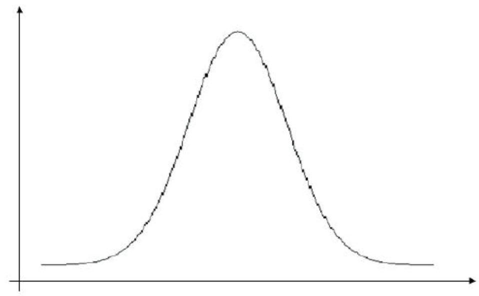
Internal Noise (Johnson-Nyquist Noise)

Sometimes referred to as thermal noise or white noise, it is a result of the thermal motion of the charge carriers within the component. The level of noise is dependent on the resistance and temperature of a component and is consistent across all frequencies, making it irreducible.

Johnson noise is proportional to the bandwidth, and its variation is Gaussian distribution.

This can be derived from the power spectral density. Gaussian implies an even distribution on either side of a centre point, with the centre point representing the average or mean. It conforms to a is a bell-shaped or normal curve, as shown in Figure 1.

Figure 1 – Example Gaussian distribution curve



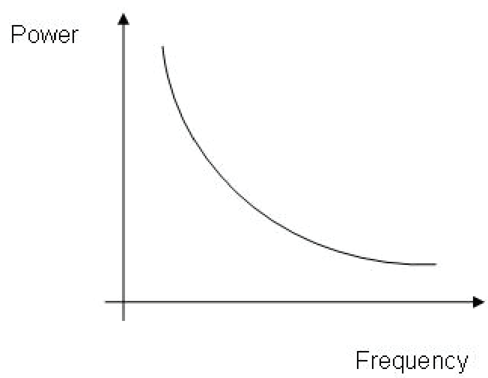
Shot Noise

The discrete nature of the electrons, constituting the current also introduces noise in the component. This becomes particularly significant in very low current applications. This noise is also white and irreducible.

Flicker Noise

While Johnson and Shot Noise are independent of circuit and component design, flicker noise is not. Flicker noise (also known as pink noise), prevails at low frequencies and stems from the transient fluctuations in the component's performance. It follows a trend similar to that of power (P) = 1/f where f is frequency. Consequently, the power of flicker noise decreases as frequency increases, as illustrated in Figure 2.

Figure 2



info@IQDfrequencyproducts.com IQDfrequencyproducts.com
Head Office UK: +44 (0) 1460 270200 Germany: +49 (0) 7942 945 4912
IQD Frequency Products Ltd, Station Road, Crewkerne, Somerset TA18 8AR UK

External Noise

This represents another form of interference. Examples include the 50Hz mains power line, capacitive and magnetic coupling. This can be exacerbated by poor circuit design, without proper forethought, this can be a problem.

Random Walk

This is intrinsic to the crystal structure itself, including environmental sources such as shock and vibration. These are long-term factors that affect the structure of the crystal itself and, for the immediate discussion, can be ignored. Random walk is typically defined as being less than 10Hz.

Quantifying Noise

Generally given as a Signal to Noise Ratio (SNR), defined in decibels as SNR= 20log10 (Vs2/VN2) (1). Where Vs and VN are the rms voltages for the signal and the noise respectively.

Phase Noise

For this discussion, we are interested in a uniformly periodic waveform oscillating about a given point, such as a square wave oscillating between ground (0V) and the supply voltage (Vs). We will consider the point at which the output rises through ½ Vs as our threshold reference voltage, using this value for measurement of the rising edge of the pulse. We do not consider any increase from 0V on our rising edge, as this may be random noise. Alternatively, we can consider a sine wave symmetrical about the horizontal X-axis where x=0 is our reference point of measurement, the 0V line.

Effectively, we are seeking the phase difference between the original waveform and the received waveform, i.e. the jitter of the signal. Jitter is described in terms of time or Unit Intervals, whereas phase noise would be described in terms of radians or degrees.

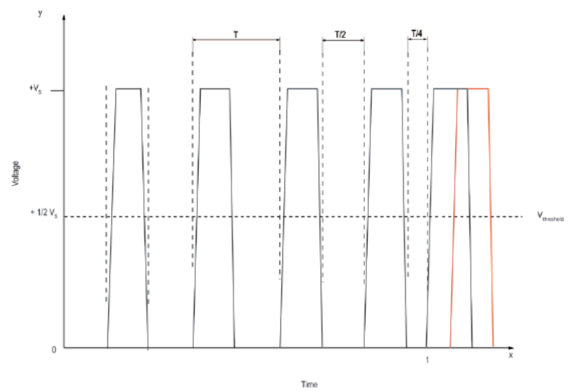
For example, consider a uniform square wave that oscillates between 0V and +Vs at a frequency of 1MHz, However, induced into the circuit is noise that causes the signal reaches ½ Vs early.

As shown in Figure 3, the final waveform crosses the threshold voltage ½ Vs faster than the previous waveforms due to noise causing the waveform to arrive early. In this case, the time spent at 0V was half the time of the previous waveform.

Using: T=1/f (2)

Where a whole cycle takes 1μs. So this waveform arrived 250ns early. This is a jitter of 250ns or a phase shift of ½ π or 90°.

Figure 3



An example that can be analysed mathematically to give a clearer description of phase shift, and thus jitter, is a sinusoidal waveform. A sinusoid can be written in the form: $f(t) = A\sin(\omega t + \theta)$ (3) where A is the max amplitude of the wave, $\omega = 2\pi f$ and θ is the phase shift.

Example:

Consider the following scenario, x is a sine curve with a frequency of 1Hz, and the waveform can be described in an equation of $x=\sin(2\pi t)$. However, noise is present, causing the wave to shift out of phase, as shown in Figure 4, 5 and 6.

We use a threshold voltage of 0V, and the time is recorded when the wave crosses the horizontal X-axis. The time is measured as 0.4375s when it crosses the X-axis indicating a jitter of 0.0625s. From this, we can work out the phase shift using the below calculation:

$f(t) = A\sin(\omega t + \theta)$

$f(t) = A\sin(2\pi ft + \theta)$

$f(t) = A\sin(2\pi t + \theta)$ as $f = 1$

$f(t) = A\sin(2\pi \times 0.4375 + \theta)$ as wave is 0.4375s early

$f(t) = \sin(2\pi \times 0.4375 + \theta)$ as $A = 1$

$0 = 2\pi \times 0.4375 + \theta$ at $f(t) = 0$

$0 = 0.875\pi + \theta$

$-\theta = 0.875\pi$

$\theta = 0.125\pi$

$\theta = 1/8\pi$ phase shift

Figure 4 – Out of phase waveform

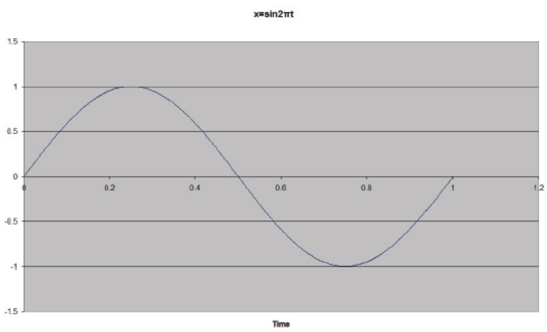


Figure 5 – Waveforms on same axis

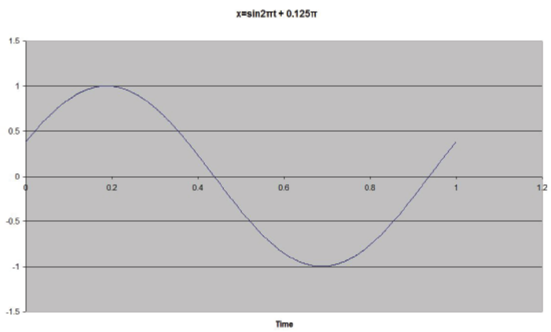
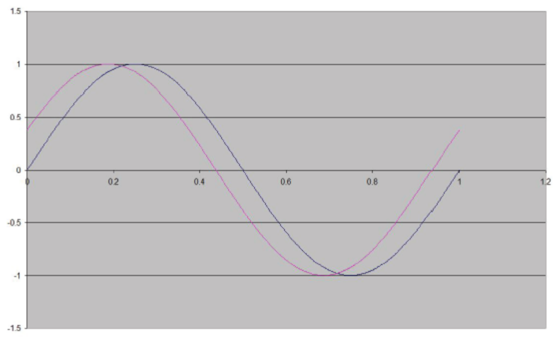


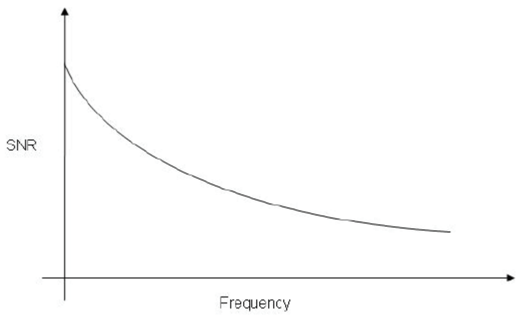
Figure 6 – The pink waveform is out of phase



Phase Noise Plot

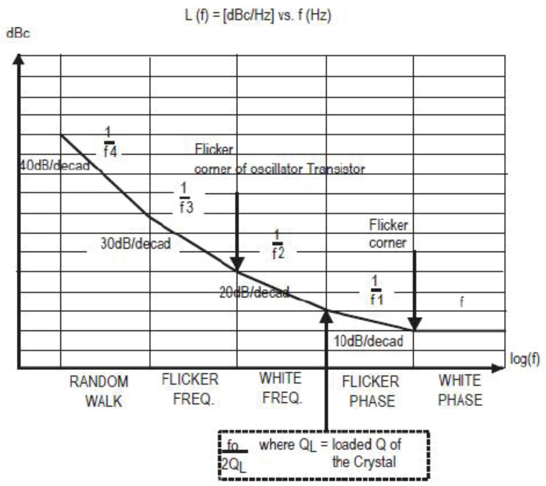
In the previous examples a single incident of noise was analysed. However, it is also useful to examine how the Signal to Noise Ratio (SNR) varies as the frequency or the noise changes. This is plotted on a graph with the value of the SNR shown on the Y-axis and the distance from the base frequency represented on the X-axis. The further the frequency is away from the base frequency, the smaller the SNR will become, as shown in figure 7.

Figure 7



From the graphs, you can determine various points of interest, such as the 3dB frequency where the power of SNR is halved. This enables the creation of a graph showing phase noise verse offset.

Figure 8 – Noise over Frequency Graph



The graph in Figure 8 breaks down the sources of phase noise experienced by a crystal oscillator. The phase noise plot is separated into five main areas, with the distance from the base frequency on the horizontal X-axis and SNR on the vertical Y-axis. You can observe the flicker corner, the point at which flicker noise becomes a negligible factor in the signal. At this point, all noise above this corner frequency becomes irreducible. This is very similar to the previous graph, with the regions of noise labelled.

Measuring Jitter

Having presented the basic concepts of jitter, the principles governing it are logical and straightforward; in fact, it is a measurement of the difference between an ideal and non-ideal waveform. Although, actually making the measurements can be quite tedious. In the previous examples, we compared the measured signal to a theoretically ideal signal. However, in the real world, no signal is perfect and to make measurements you must have a clean signal to compare it with, i.e. a signal with little noise.

Period and Cycle to Cycle Jitter

Period jitter is the difference between the position where the clock cycle should be, and the point at which it appears. This is the time difference between when the ideal pulse should have arrived and when the pulse actually arrives.

Cycle to cycle jitter is the difference between two consecutive clock cycles, where the induced jitter in the system causes a change to the next ideal signal.

For example, consider a uniform waveform oscillating between ground and +Vs with a nominal period T. However, the jitter causes the waveform to arrive at a different time (t). We can express the cycle to cycle jitter as T-t. Measuring cycle to cycle jitter is hard as the period of the ideal waveform is based on the period of the previous waveform. To find the next cycle to cycle jitter, we would compare the period of the next cycle with the previous period. This usually requires the use of high-speed timing devices capable of measuring signals faster than the frequency of the waveform.

One method is to take the average of the nominal frequency over a long period of time to use as the reference. This assumes that the noise is random and has a Gaussian distribution curve with its mean as 0. It follows that the average frequency will not differ from the theoretical nominal frequency. Then, measure small changes to this average over short periods of time to determine the jitter of the signal. However, problems may arise considering factors such as heating, changing environmental factors, and random walk.

Another way is to use a reference signal, a clean source with the same nominal frequency as the component of interest. The source must have a controllable frequency, and it is crucial to eliminate all external interference with a suitable feedback system.

Additionally, a feedback loop needs to be established to maintain the mean long-term frequencies, this is called phase locking. You 'lock' the controllable source to the component of interest, comparing their long-term average frequencies.

This method removes the problem of random walk, allowing the measured signal to walk while the controllable source 'walks' an equal amount due to the feedback loop.

Even though the component is locked into a loop, it can still jitter. For measurement purposes, we are interested in when the signal crosses the threshold voltage. The defined point of interest; previously given as 1/2 of Vs on the X-axis in the examples.

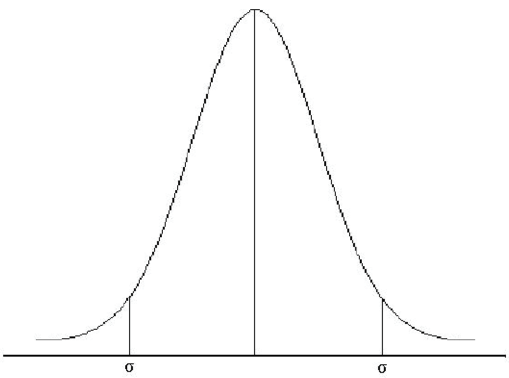
We are interested in the points when the jitter has caused time differences in the threshold voltage's of both components. The difference in these two times will indicate the jitter of the component. From these values we can plot a histogram of the values recorded.

Peak to Peak Jitter

Another way of describing the jitter measured is by showing the peak to peak value, by taking a reasonably large multiple of the rms value. A common choice is to use a peak to peak (pk-pk) value of 14 σ.

Any values that fall outside of this will be sufficiently rare for them to be almost negligible. You take a system that is bounded between two points, then the worst-case scenario is just the peak to peak values between the bounded edges of the system. However, note this is making the assumption that the bounded edges do not allow any fluctuation in the output level above or below the defined edges.

Figure 9



Root Mean Jitter (σ)

The recorded data is presented as a Gaussian distribution curve as per the example shown, that is to say it follows a normal distribution pattern. This is usually the case with random sources of jitter.

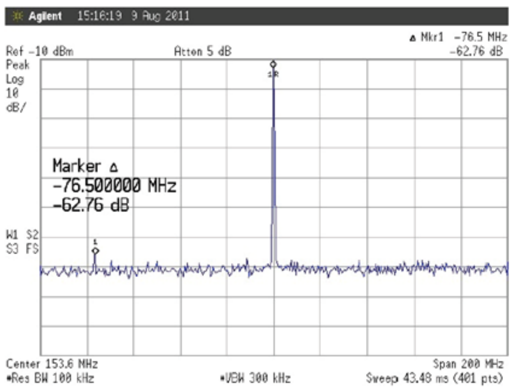
An interesting observation can be made from the Gaussian distribution of this data. We can establish the root mean square jitter σ by its width. Furthermore, we can also observe that the mean jitter is 0, this will only be the case for idealised Gaussian distributions.

For systems that do not fit either the Gaussian or bounded scenario, we use a procedure similar to that of the one use for the Gaussian system. We take the mean value of the sample, and from this point, move sufficiently far away that jitter at these points are rare enough to be considered negligible.

Frequency Analysis of Jitter

Another way to measure jitter in the frequency domain is usually through the use of a spectrum analyser. Again, we compare to the clean noise free source as mentioned above, both phase locked to allow for walk. In an ideal world, we will see just one peak response on the display, however in reality it will show a clear signal that will have a skirt on either side; these skirts are a product of the jitter corrupting the signal. There may also be low amplitude spikes or spurs present either side usually due to pink noise.

Figure 10 – An example spectrum analysis plot of jitter, including the defined spike of the main signal and the skirts as the waveform widens and moves away from the main frequency.



Quantifying Jitter

Above we showed how it was easy to quantify noise through the use of a signal to noise ratio, while with jitter, we usually express it as the time difference between the expected pulse and the moment the pulse actually arrives. For systems that are operating in the megahertz range, it is common to quantify jitter measurements in picoseconds.

Jitter in Oscillators

Jitter in oscillators should arise only from random sources, if they are correctly designed and the output frequency matches the natural resonant frequency of the crystal. The random jitter in the oscillators should be sufficiently small, as to be measured in picoseconds.

This should be the case for all oscillators, even for those whose output is a square wave signal derived from the sine-wave output of the crystal oscillator. The jitter in programmable crystal oscillators is generally larger due to the way in which their output frequency is generated.

They usually use a phase locked loop (PLL) method of frequency generation, and this can increase their susceptibility to jitter, usually in the order of 100ps rms. It is useful to consider the jitter that may be induced into the system from external systems.

If a low jitter signal is essential to the workings of the system, then choosing a component with low jitter values isn't enough, and a decision should be made to design a circuit that minimises jitter. For example, shielding the component and circuitry from interference may be sufficient, or placing a simple RC-filter in the supply line may help attenuate all high voltage ripples from the power supply. The output signal from the oscillator may be pure and clean, however the circuit in which it lies may be easily susceptible to noise and jitter.

Jitter Effects

As most digital systems rely on a universal clock bus, we are concerned in whether a circuit can tolerate any slight changes in clock pulse timing.

In digital communication systems, the encoded data is usually sent over long distances and it is then decoded once received. However, there needs to be a common clock to allow for the pulse to be decoded, and if the clock of either is affected by jitter, there may be some loss in data integrity from the source. Again, it is worth considering your application before choosing an appropriate crystal oscillator.