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 nature of the signal it easy to predict when the next pulse will arrive. You could if you wanted set up a system that utilised the nature of this pulse; for instance if the time between two pulses was some multiple of a second you could make a very simple timing device from 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 early.
This is essentially jitter and can be quite problematic by causing system degradation.

Noise Basics
Noise is any unwanted information within a signal from internal or external sources, some are unavoidable while others can be removed from the system.

Internal Noise (Johnson-Nyquist Noise)
Sometimes referred to as thermal noise or white noise and 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 the same at all frequencies and is thus irreducible. Johnson noise is proportional to the bandwidth and the variation of it is Gaussian in nature. This can be derived from the power spectral density. Gaussian means it is evenly distributed either side of a centre point, with the centre point being the average or mean. It is a bell or normal curve as per figure 1.

Shot Noise
The discrete nature of the electrons that comprise the current also induces noise in the component. This becomes of great significance in very low current applications. This is also white and irreducible.

Flicker Noise
Although Johnson and Shot Noise are independent of circuit and component design, flicker noise is not. Flicker noise (also known as pink noise) predominates at low frequencies and is due the transient fluctuations of the components performance. It follows a trend similar to that of power = 1/f where f is frequency. It follows that the power of flicker noise tends to 0 as frequency increases. Figure 2.

External Noise
This is a 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 within the crystal structure itself, including environmental sources such as shock and vibration. These are long

Figure 1 - Example Gaussian distribution curve

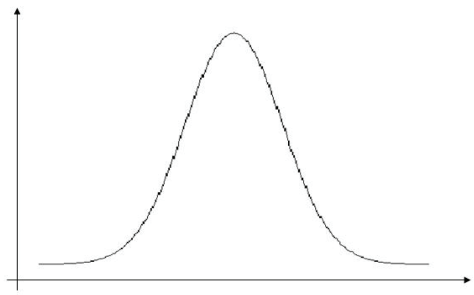


Figure 2

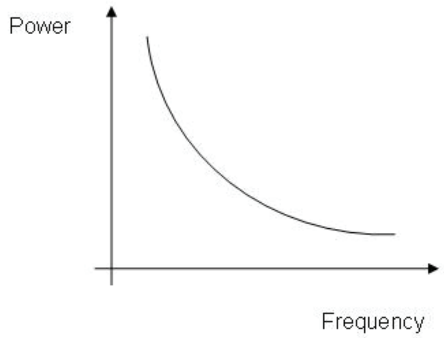
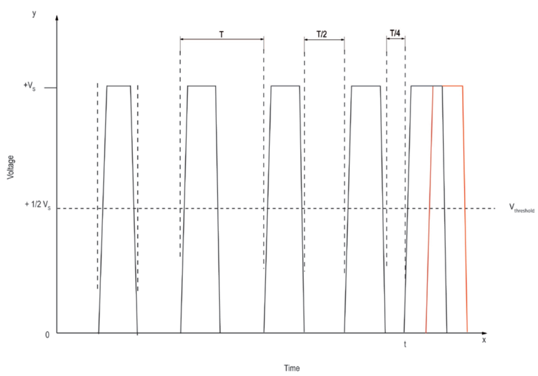


Figure 3



Contact Details:
UK: +44 (0)1460 270200
Germany: 0800 1808 443
France: 0800 901 383
USA: +1.760.318.2824
Email: info@iqdfrequencyproducts.com
Web: www.iqdfrequencyproducts.com

term factors that affect the structure of the crystal itself and can for this immediate discussion be ignored. Random walk is usually defined as being less than 10Hz and not jitter.

Quantifying noise

Generally given as a Signal to Noise Ratio (SNR): Defined in a 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 uniform periodic waveform oscillating about a given point. For example, 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 and use 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.
We are effectively looking for 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 a noise that means the signal reaches ½ Vs early.
As can be seen 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)
We know 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°.
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 whose frequency is 1Hz. The waveform has an equation of $x=\sin 2\pi t$. However noise is present and causes the wave to move out of phase. Figure 4, 5 and 6.

We have a threshold voltage of 0V, 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. This is a jitter of 0.0625s. From this we can work out the phase shift. From (3):

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

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

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

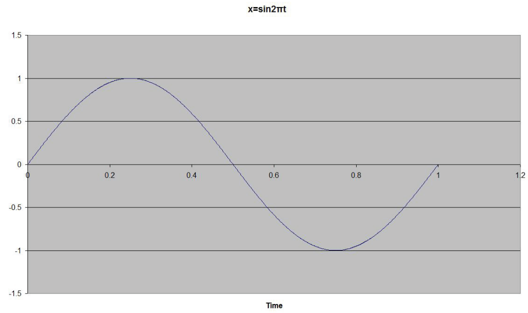


Figure 5 - Waveforms on same axis

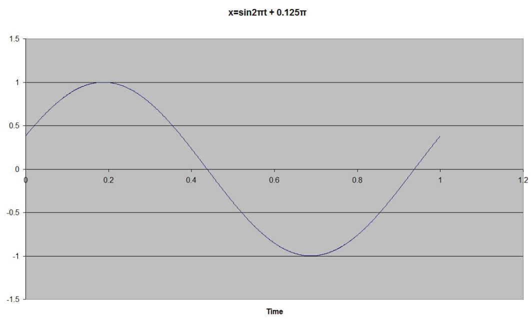


Figure 6 - The pink waveform is out of phase

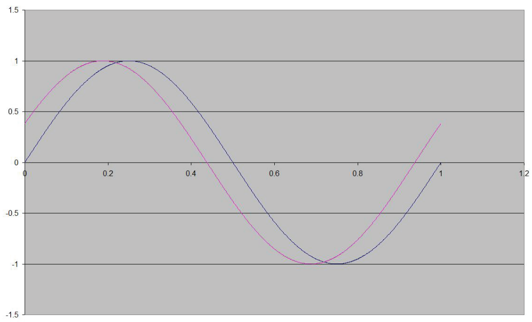
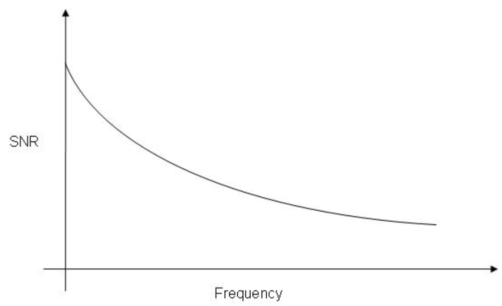


Figure 7



Contact Details:
UK: +44 (0)1460 270200
France: 0800 901 383
Email: info@iqdfrequencyproducts.com
Germany: 0800 1808 443
USA: +1.760.318.2824
Web: www.iqdfrequencyproducts.com

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, figure 7.
From the graphs you can work out where various points of interest are for example the 3dB frequency where the power of SNR is halved. This enables a graph to be drawn up showing phase noise verse offset.
The graph in figure 8 breaks down the sources of phase noise experience by a crystal oscillator. The phase noise plot is separated into five main areas with 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 the fact that it's a measurement of the difference between an ideal & non-ideal waveform. However actually making the measurements can be quite involved.
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 with, i.e. a signal with very little noise.

Period and Cycle to Cycle Jitter

Period jitter is the difference between the position the clock cycle should be and the point at which it appears to be. This is the time difference between when the ideal pulse should have arrived and when the pulse actually arrived.
Cycle to cycle jitter is the difference between two consecutive clock cycles whereby the jitter induced into the system causes a change to the next ideal signal.
For example consider a uniform waveform that is oscillating between ground and +Vs with a nominal period T. However the jitter causes the waveform to arrive at a time instead. We can say the cycle to cycle jitter is T-t. The cycle to cycle jitter is hard to measure 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 that are able to measure faster signals 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. You are assuming 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 give you the jitter of the signal. However this can lead to problems when you consider 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 will need to have a controllable frequency. We will need to eliminate all external interference with a suitable feedback system. We also

Figure 8 - Noise over Frequency Graph

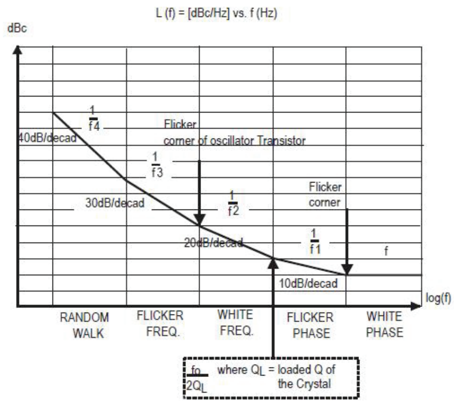


Figure 9

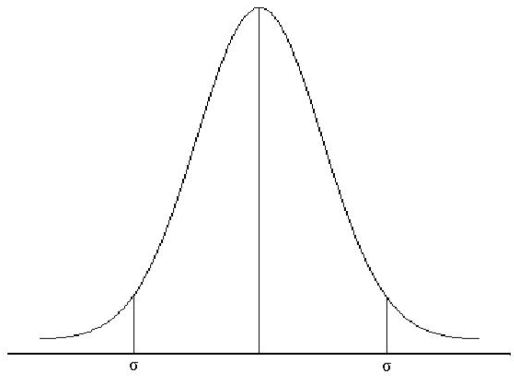
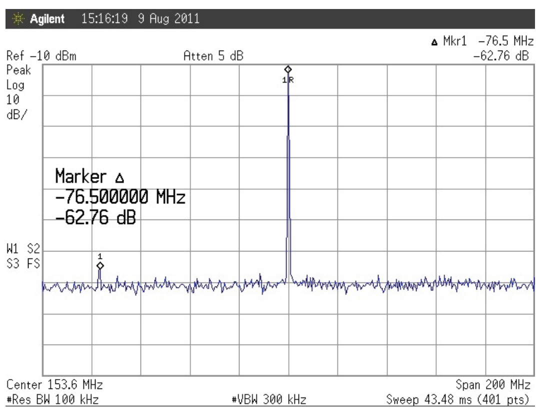


Figure 10 - An example spectrum analysis plot of jitter



Contact Details:
UK: +44 (0)1460 270200
France: 0800 901 383
Email: info@iqdfrequencyproducts.com
Germany: 0800 1808 443
USA: +1.760.318.2824
Web: www.iqdfrequencyproducts.com

need to create a feedback loop to keep their mean long term frequencies the same, this is called phase locking. You 'lock' the controllable source to the component of interest comparing their long term average frequencies. This removes the problem of random walk as it allows 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. (Our defined point of interest; in the previous examples was given as 1/2 of Vs on the X axis.)
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 show us the jitter of the component. From these values we can plot a histogram of the values recorded.

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. Further we can also observe that the mean jitter is 0, this will only be the case for idealised Gaussian distributions.

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 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.
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 show jitter is to measure in the frequency domain 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 of the signal due usually to pink noise.
Figure 10. Note 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 pulse actually arriving. 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.

Contact Details:
UK: +44 (0)1460 270200
Germany: 0800 1808 443
France: 0800 901 383
USA: +1.760.318.2824
Email: info@iqdfrequencyproducts.com
Web: www.iqdfrequencyproducts.com