Phase Noise and Jitter in Crystal Oscillators

Technical Note

Introduction

Understanding the performance of crystal oscillators is essential for designing precise timing systems. Two critical parameters that define oscillator stability are Phase Noise and Jitter. These terms are often used interchangeably, but they describe stability in different domains—frequency and time, respectively. This technical note clarifies these concepts and examines their origins, measurement techniques, and implications for oscillator performance.

Understanding Phase Noise and Jitter

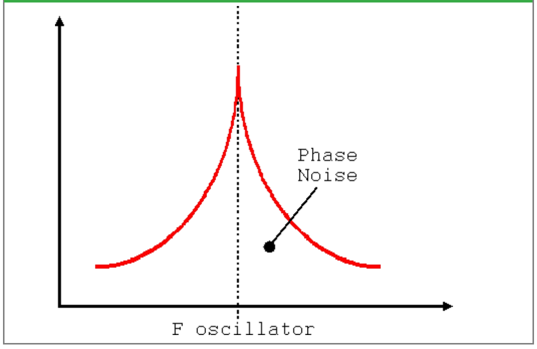
Phase Noise: Frequency Domain Perspective

Phase Noise characterizes the frequency stability of an oscillator. It distinguishes between:

- Random (Stochastic) Noise:
  Unpredictable fluctuations.
- Induced/Repetitive (Deterministic) Noise:
  Predictable, often periodic disturbances.

In the frequency domain, we use a spectrum analyser to observe the oscillator's spectral content over a defined frequency range (see Fig. 1).

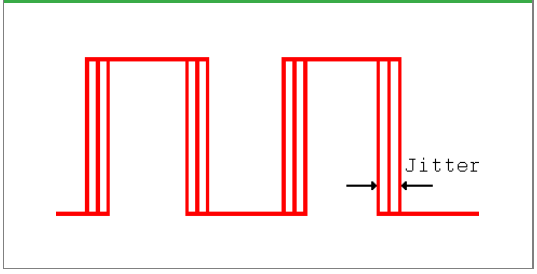
Fig. 1



Jitter: Time Domain Perspective

Jitter describes the oscillator's stability in the time domain. It aggregates all noise sources and shows their cumulative effect over time. An oscilloscope is used to visualise the output waveform over a time window (see Fig. 2).

Fig. 2:

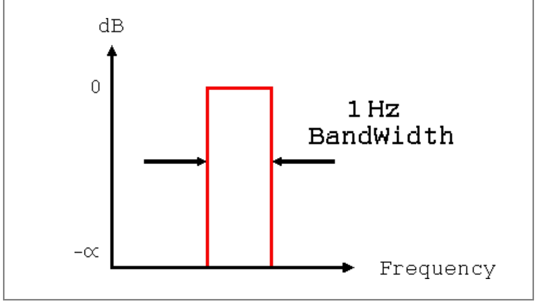


Spectral Density and Phase Noise Measurement

To understand Phase Noise, we must first grasp Spectral Density. Imagine a theoretical band-pass filter with the following ideal characteristics (Fig. 3):

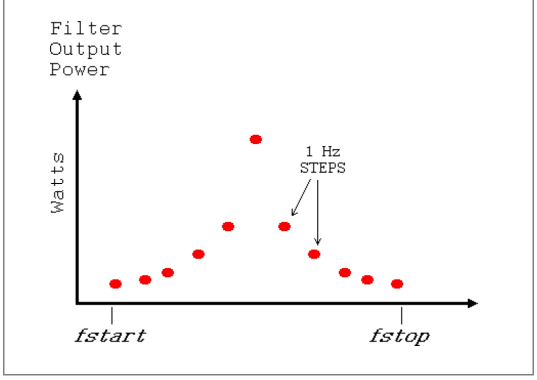
- Passband gain = 1
- Infinite stopband attenuation
- Passband width = 1 Hz
- Vertical transition from passband to stopband
- Tunable center frequency in 1 Hz steps

Fig. 3



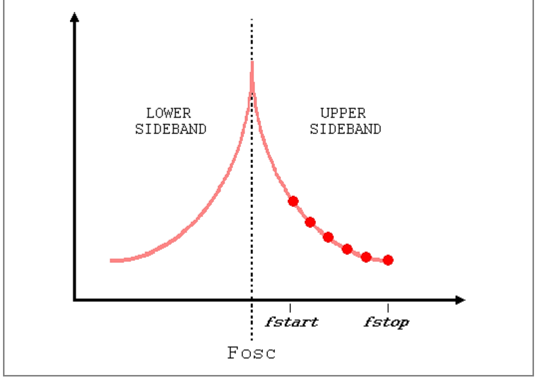
By sweeping this filter from a start frequency f_{start} to a stop frequency f_{stop} in 1 Hz increments, and measuring the output power at each step, we generate a plot of Signal Power Spectral Density in watts per Hz (Fig. 4).

Fig. 4



When applied just above the oscillator frequency F_{osc} (Fig. 5), this method measures the Single Sideband (SSB) Noise Power Spectral Density. Since signals above F_{osc} not harmonically related are considered noise, we refer to this as SSB Noise Density, typically expressed in dBW/Hz (decibels relative to 1 watt per Hz).

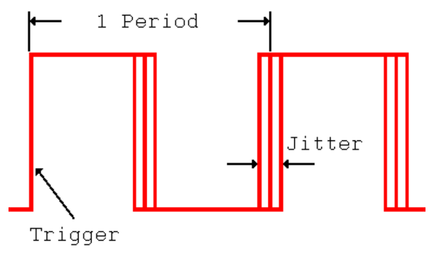
Fig. 5



Linking Jitter to Phase Noise

For a stable crystal oscillator, observing the output waveform on an oscilloscope (triggered on rising edges) reveals slight timing variations or "jitter" (Fig. 6). If this jitter is much smaller than one full period, it is attributed to Phase Noise rather than frequency drift.

Fig. 6

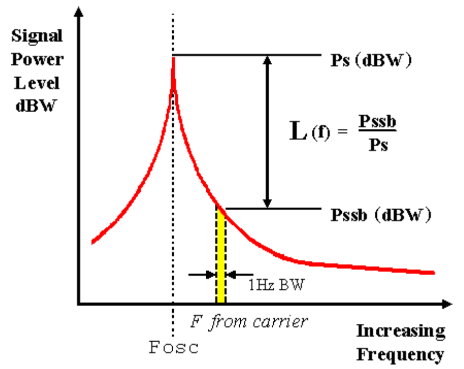


This leads to the formal definition of Phase Noise:

$$L(f) = \frac{\text{Power density in a 1 Hz sideband}}{\text{Total signal power}}$$

Phase Noise is expressed in dBc/Hz (decibels relative to the carrier per Hz) (Fig. 7).

Fig. 7

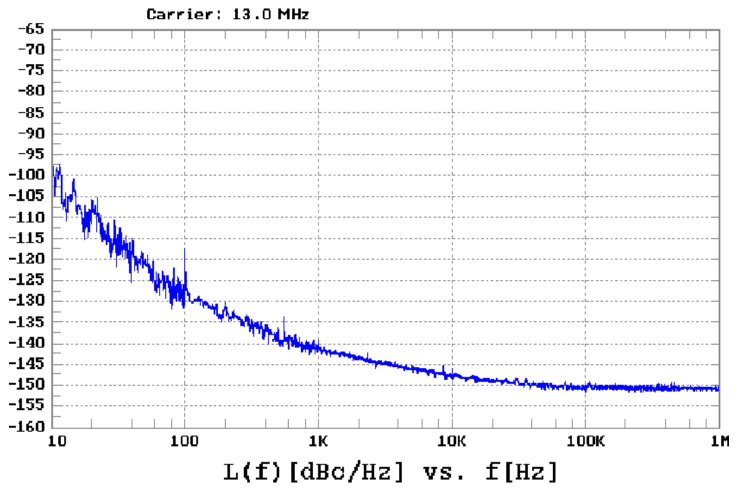


Real-World Example: 13.0 MHz Crystal Oscillator

Fig. 8 shows a Phase Noise plot of a real 13.0 MHz crystal oscillator. By comparing it to an idealized Phase Noise model (Fig. 9), we can identify key contributors:

- Flicker corner of buffer stage: ~5 kHz
- Loaded Q of the crystal (Q ≈ 38,000): ~170 Hz
- Flicker corner of oscillator transistor: ~12 Hz
- Random walk: ~0.1 Hz (extrapolated)

Fig. 8



Sources of Phase Noise

Noise Type	Description
White Phase	Thermal (Johnson) noise from buffer amplifiers, resistors, and shot noise.
Flicker Phase	Pink noise, primarily from buffer amplifier flicker noise.
White Frequency	Carrier noise, mainly from the crystal's RLC network.
Flicker Frequency	Intermodulation of carrier noise and flicker phase noise.
Random Walk	Intrinsic quartz/electrode noise and environmental effects (shock, vibration, temperature).

External influences also affect Phase Noise performance, including:

- Power supply noise
- Ground loop currents
- Control voltage fluctuations
- Load variations
- Mechanical vibration
- Electromagnetic interference

Voltage Considerations

Since Phase Noise is expressed in dBc (power relative to the carrier), voltage implications are significant. For example, a 3.3V CMOS oscillator with a noise floor of -150 dBc has a noise voltage of approximately 104 nV peak-to-peak. This highlights the importance of minimizing noise sources in sensitive designs.

Conclusion

Phase Noise and Jitter are fundamental metrics for evaluating oscillator performance. Understanding their origins—both intrinsic and external—enables engineers to design more robust and precise timing systems. By analyzing spectral and time-domain behavior, we can identify and mitigate noise sources to improve oscillator stability.

For further technical support or detailed application guidance, please contact us directly.