Tópicos sobre Ruído de Fase em Teste e Medicação

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Agenda

• Phase Noise Basics
  • What is Phase Noise?
  • Review: AM, PM & Phase Noise
  • Theory & Mathematics of Phase Noise
  • Noise Sources that Contribute to Phase Noise

• Phase Noise Applications
  • Radar
  • Digital Communications

• Phase Noise Measurements
  • Phase Detector Techniques
  • Reference Source/PLL Measurement Method
  • Frequency Discriminator Measurement Method
  • Cross-correlation

• Conclusion
What is Phase Noise?

**FREQUENCY INSTABILITY**

**Long-term frequency instability**
- Slow change in average or nominal center frequency

**Short-term frequency instability**
- Instantaneous frequency variations around a nominal center frequency

Phase noise is generally considered the short-term phase/frequency instability of an oscillator or other RF/µW component.
Two categories of PM signals:

Random Signals:
- Noise which modulates the carrier
- Produces continuous spectral density plot similar to broadband noise
- Measured power is proportional to the bandwidth used

Deterministic:
- Discrete signals due to repetitive, constant rate events
- Spurs related to power line frequency, AC magnetic fields, mechanical vibration, etc.
- Measured power constant independent of bandwidth
What is Phase Noise?

**IDEAL VERSUS REAL-WORLD SIGNALS**

**Ideal sinusoidal signal**

\[ V(t) = A_o \sin(2\pi f_o t) \]

where

\[ A_o = \text{nominal amplitude} \]
\[ f_o = \text{nominal frequency} \]

**Real sinusoidal signal**

\[ V(t) = [A_o + E(t)] \sin[2\pi f_o t + \phi(t)] \]

where

\[ E(t) = \text{random amplitude fluctuations} \]
\[ \phi(t) = \text{random phase fluctuations} \]
What is Phase Noise?

- Phase fluctuation of an oscillator produced by different random noise sources is phase noise
  - Just phase modulation with noise as the message signal
- Mostly concerned with frequency domain where phase noise is simply noise sidebands or skirt around “ideal” delta function from sinusoidal oscillator
- Because PM is symmetrical in magnitude around center frequency, can measure a single noise sideband (SSB)
What is Phase Noise?

HOW TO DEFINE PHASE NOISE MEASUREMENTS

Three elements:

- Upper sideband only, offset frequency \( (f_m) \) from carrier frequency \( (f_0) \)
- Power spectral density, in 1 Hz BW
- PSD *relative* to carrier power in dBC

dBC/Hz @ offset frequency \( f_m \) from specified carrier frequency \( f_0 \)
In the time domain, rms phase deviation is called \textit{jitter}.

Frequently, people concerned about jitter deal with clock signals, and thus are more concerned about measuring square wave type signals as opposed to the sinusoids we've been dealing with.

To relate rms phase deviation to jitter, we can use the following mathematical relation:

\[
\text{jitter (seconds)} = \frac{\phi_{\text{RMS}}}{2\pi} \left[ T_{\text{period (seconds)}} \right] = \frac{\phi_{\text{RMS}}}{2\pi f_c}
\]
Log Scaled Phase Noise

**PHASE NOISE ON A SPECTRUM ANALYZER**

- As we saw before, single sideband phase noise $\mathcal{L}(f)$ is a relative power measurement—we measure the power density of the noise sideband relative to the power of the carrier:

\[
\frac{P_{SSB}(W/Hz)}{P_c(W)} = \frac{1}{2} \phi_{rms}^2 \frac{(rad^2)}{Hz} = \mathcal{L}(f) \frac{(rad^2)}{Hz}
\]

- These ratios (relative power measurements) are suited quite well to spectrum analyzers—which measure signals using a log-transformed power scale

- Context matters because $\mathcal{L}(f)$ is used for both linear units and log-transformed phase noise (in dBc/Hz)

- The log scale (dB) allows us to replace the division of the carrier with subtraction and gives us units of dBc/Hz

\[
\mathcal{L}(f) = P_{\text{noise}} \text{ (dBm/Hz)} - P_{\text{carrier}} \text{ (dBm)} = -121.28 \text{ dBc/Hz}
\]

1 kHz measurement bandwidth using noise density marker (generally normalized to 1 Hz)
Phase Modulation (PM) vs. Amplitude Modulation (AM)

• Phase noise ($\mathcal{L}(f)$) is a **phase phenomenon**
  
  • Simply PM of carrier signal with noise message signal
  
  • Deriving narrowband PM mathematically shows extreme similarities between AM & PM

\[
\phi(t) = \text{time varying random noise signal with randomly varying frequency & amplitude}
\]
\[
cos(\omega_c t) = \text{ideal carrier sinusoidal signal from oscillator}
\]
\[
cos(\omega_c t + \phi(t)) = \text{real signal with phase noise on it}
\]

Recall: $\cos(\alpha + \beta) = \cos(\alpha)\cos(\beta) - \sin(\alpha)\sin(\beta)$

where: $\alpha = \omega_c t$ and $\beta = \phi(t)$

Small-angle approximations: $|\phi(t)| < \frac{1}{5}\text{rad}$ and from this $\cos(\phi(t)) \approx 1$ and $\sin(\phi(t)) \approx \phi(t)$

Result:

\[
cos(\omega_c t + \phi(t)) = cos(\omega_c t) - \phi(t)\sin(\omega_c t)
\]

Noise that modulates phase of carrier becomes **amplitude modulation** of carrier.
PM vs. AM

**AM vs. Narrowband PM on Spectrum Analyzer**

- SSB noise contains both AM & PM components
- Compare double sideband (DSB) AM with narrowband PM signal where both have $\phi(t)$ as sinusoidal message/modulating signal:

  **DSB AM:**
  \[
  [1 + \phi(t)]\cos(\omega_c t) = \cos(\omega_c t) + \phi(t)\cos(\omega_c t)
  \]

  **Narrowband PM:**
  \[
  \cos(\omega_c t + \phi(t)) = \cos(\omega_c t) - \phi(t)\sin(\omega_c t)
  \]

  Difference is just a phase shift

*DSB AM signal with 0.8% modulation index, AM Rate=10 kHz

*Narrowband PM signal with $\Delta \phi_{pk} = 0.2 \text{ rad}$ index, PM Rate=10 kHz

- Because legacy spectrum analyzer shows magnitude spectrum, AM & narrowband PM look identical. Thus, **need to remove AM component** to accurately measure only the phase noise component of total noise
**Types of Noise Contributing to Total Phase Noise**

**THERMAL NOISE (JOHNSON-NYQUIST NOISE)**

Thermal noise is “white” (i.e., same magnitude power spectral density at all frequencies, or $-174 \text{ dBm/Hz}$)

\[ N_p = \frac{-204 \text{ dB (Watts)}}{\text{Hz}} = -174 \text{ dBm/Hz} \]

For $T = 290 \text{ K}$

- $k = \text{Boltzmann's constant}$
- $T = \text{temperature (K)}$
- $B = \text{bandwidth (Hz)}$
- $N_p = \text{Noise Power Density} = kT$
Types of Noise Contributing to Total Phase Noise

**1/F “MODULATION” NOISE & THERMAL NOISE**

- Beyond thermal noise floor (approx. constant spectral density), another contributor to total phase noise is inversely proportional to frequency ($\propto 1/f$)
  - Exhibited by virtually all electronic devices
- In devices operating at RF or µW frequencies, 1/f noise is **modulation** on carrier emerging from or passing through device
  - Wouldn’t exist in absence of device electronics (unlike thermal noise)

- On Bode plot, has easy-to-use property of **decreasing by 10 dB/decade**
- 1/f noise meets thermal noise floor (i.e., broadband noise) at 1/f crossing frequency
  - Beyond that point, thermal noise dominates & obscures 1/f still present

*Note: Broadband/thermal noise floor is not “modulation noise” by itself, until it is decomposed into equivalent AM & PM on a carrier*
Types of Noise Contributing to Total Phase Noise

ALL POWER-LAW NOISE PROCESSES IN AN OSCILLATOR

Theoretical noise processes

- Random Walk FM ($f^4$): $-40$ dB/decade
- Flicker FM ($f^3$): $-30$ dB/decade
- White FM ($f^2$): $-20$ dB/decade
- White PM ($f^0$)
- Flicker PM ($f^{-1}$): $-10$ dB/decade

Real noise processes in VCO

- $-30$ dB/decade
- $-20$ dB/decade
- $-105$ dBc

* Dr. Sam Palermo, Texas A&M
Importance of Phase Noise in Radar

Highest performance radar transceiver designs demand best phase noise to find moving targets, fast or slow.
Importance of Phase Noise in Digital Communications

QPSK EXAMPLE

Ideal QPSK constellation

Degraded signal with phase noise QPSK constellation
Symbols far from origin on I/Q constellation are spread more for given amount of phase noise on LO
Importance of Phase Noise in Digital Communications

**Signal Source as LO for Wideband Single Carrier QPSK**

- **PSG is LO**: EVM = ~1.8%
- **MXG is LO**: EVM = ~2.1%
- **EXG is LO**: EVM = ~2.1%

**Test Configuration**

1. **Test signal QPSK**
2. **Baseband M8190A**
3. **IF E8267D PSG**
4. **Upconverter**: LO = PSG/MXG/EXG, 10 GHz, x6
5. **5 GHz to 60 GHz**
6. **Oscilloscope Infinium**
Importance of Phase Noise in Digital Communications

**OFDM EXAMPLE**

- LTE uses OFDM with many subcarriers, each spaced at 15 kHz
- Lower (i.e., better) phase noise of receiver or transmitter LO **improves each subcarrier’s resolution & thus EVM performance**
- **Unlike case with wideband single-carrier modulation, OFDM requires extremely good close-in phase noise performance**
Measuring Phase Noise

**Direct-spectrum method**
- By sampling the carrier, direct-spectrum method immediately yields amplitude & phase information
  - Employed in signal analyzers & some phase noise systems
- Far less sensitive than carrier-removal method because carrier limits ceiling of system components
  - ADC full scale, receiver preamp compression level, etc.

**Carrier-removal method (phase detector in quadrature)**
- Increased sensitivity obtained by nulling carrier & then amplifying & measuring phase noise of resulting baseband signal with high-gain, low noise figure amplifiers
- Both frequency discriminator and PLL/reference source methods discussed next use carrier removal via **phase detectors in quadrature**
Direct Phase Noise Measurement with SA

PHASE NOISE APP ON X-SERIES ANALYZERS

Pros:
• Easy to configure & use
• Quick phase noise check
• Log plot
• Spot frequency (PN change vs. time)
• RMS PN, RMS jitter, residual FM
• X-Series phase noise application automates PN measurements

Cons:
• Uses less-sensitive direct-spectrum method
• Limited by internal PN floor of SA
• Caution: With older spectrum analyzers, AM noise cannot be separated from PM noise
  • In today’s modern signal analyzers, AM component is removed

N9068C X-Series Phase Noise Application
Phase Detector Techniques

- Frequency-discriminator & reference source/PLL methods both use phase detector as heart of system for absolute measurements.
- Phase detector also enables residual phase noise.
- Phase detector takes two input signals & compares phase:
  - Output of phase detector is DC voltage proportional to delta phase of input signals ($\Delta \phi$).
  - Constant of proportionality, $K$, has units of volts per radian ($V$/rad) & must be measured.
- Phase detectors also tend to suppress AM noise.

\[ \Delta V_{\text{out}} = K \Delta \Phi_{\text{in}} \]
Double-Balanced Mixer as Phase Detector

**THE MATHEMATICS**

- Double-balanced mixers produce sinusoids at sum & difference frequencies of two input signals, \( x(t) \) & \( y(t) \)
- If both signals are at same frequency \( \omega_0 \) & 90° offset, yields 0 Hz (DC) & high-frequency (2\( \omega_0 \)) sum term that is removed using low-pass filtering (LPF)
- After LPF, resulting DC term varies in amplitude as cosine function of \( \Delta \phi \) of the two signals
  - This is a delta-phase to voltage converter or phase detector

\[
x(t) = A \sin[\omega_0 t + \phi_x(t)] \\
y(t) = B \sin[\omega_0 t + \phi_y(t)]
\]

\[
x(t) \times y(t) = \frac{1}{2} AB \cos[\phi_x(t) - \phi_y(t)] - \frac{1}{2} AB \cos[2\omega_0 + \phi_x(t) + \phi_y(t)]
\]

\[V_{out} \propto \frac{1}{2} AB \cos[\phi_x(t) - \phi_y(t)]\]

\( \Delta \phi \) to Voltage Converter ("Phase Detector")
Double Balanced Mixer as a Phase Detector

**IMPORTANCE OF QUADRATURE**

- Phase detector’s cosine output voltage, \( \cos(\Delta \phi) \), is nonlinear
  - Want to linearize to create linearly proportional relationship between \( \Delta \phi \) & output voltage
- If DUT & reference signal inputs to phase detector are offset \( \pm 90° \), output is zero volts & derivative of cosine function is maximized (i.e., maximum sensitivity)
- As \( \Delta \phi \) increases or decreases about 90°, output voltage changes approximately linearly with \( \Delta \phi \) and having slope or derivative K (also known as *proportionality constant* in V/\( \text{rad} \))
- Quadrature also allows high AM suppression (up to 30 dB) so are measuring only PM
- After characterizing K, get output voltage that varies linearly with delta phase: \( V = K \Delta \phi \)
  - *This is a phase detector!*

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**Phase detector output voltage vs. delta phase**

- **Slope is K**
- **V_{out}**
- **\( \Delta \phi \)**
- **180°**
- **90°**

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**Piece-wise Linear Region about quadrature (\( \Delta \phi = 90° \))**

where \( V = K \Delta \phi \)
Reference Source/PLL Method for Absolute Measurement

- Absolute phase noise measurement is direct characterization of DUT (e.g., an oscillator) performance, inclusive of reference source
  - A one-port measurement
- Reference-source/PLL method is phase-detector technique that uses a phase-locked loop (PLL) system to set & keep DUT & reference sources in quadrature
  - Keeps phase detector in linear region
- Limited by noise floor of system itself if have an ideal reference source with zero phase noise
Frequency Discriminator Method for Absolute Measurement

- An absolute (one-port) measurement that also uses a phase detector
- Signal from DUT is split into two paths
  - Signal in one path is delayed relative to the other
- Delay line converts **frequency fluctuations** into **phase fluctuations**
  - Delay line (or phase shifter) is adjusted so that inputs to mixer are in quadrature
- Phase detector converts phase fluctuations into voltage fluctuations that are analyzed using the baseband analyzer
- Less sensitive than PLL/reference-source method for close-to-carrier measurements
Cross-Correlation Technique

- Uses two phase detectors & two references to further improve phase noise floor (i.e., sensitivity)
- Two channels are uncorrelated so remove noise from references & system components through computational process (time vs. performance tradeoff)
- DUT signal is common to both channels so is perfectly correlated in both channels & kept as measurement result
- Available in Keysight E5052B SSA and N5511A Phase Noise Test System (PNTS)
Cross-Correlation Technique

TIME VERSUS PERFORMANCE IMPROVEMENT

\[
N_{\text{meas}} = N_{\text{S.U.T.}} + \left( N_1 + N_2 \right) / \sqrt{M}
\]

assuming \( N_1 \) and \( N_2 \) are uncorrelated

<table>
<thead>
<tr>
<th>( M ) (number of correlations)</th>
<th>10</th>
<th>100</th>
<th>1,000</th>
<th>10,000</th>
</tr>
</thead>
<tbody>
<tr>
<td>Noise reduction on ((N_1+N_2))</td>
<td>-5 dB</td>
<td>-10 dB</td>
<td>-15 dB</td>
<td>-20 dB</td>
</tr>
</tbody>
</table>
Keysight E5052B Signal Source Analyzer

CROSS-CORRELATION SYSTEM W/ BUILT-IN REFERENCES

- Keysight E5052B incorporates two-channel cross-correlation measurement system to reduce measurement noise
  - Can configure as:
    - Two-channel phase noise (phase detector) reference/PLL system
    - Two-channel heterodyne digital-discriminator system
- Provides excellent phase noise measurement performance for many classes of sources & oscillators
- Well suited to free-running oscillators
Residual Phase Noise Measurements

RESIDUAL MEASUREMENTS USING A PHASE DETECTOR

- Can think of as **completely different class** of measurement vs. absolute phase noise measurements
- Is “additive” or residual noise added to electronic signal
  - Often performed on two-port device (e.g., amplifier, mixer, multiplier, divider)
- Phase noise of stimulus doesn’t affect performance of residual measurement
  - Stimulus perfectly correlated at both ports of phase detector & will cancel in quadrature ($\Delta \phi = 90^\circ$ so $V = K\Delta \phi = 0V$)
  - Leaves only additional phase noise added to signal by DUT
Typical Residual Noise Measurements

HP 8349A Micro Ampl Noise Floor Using HP 70428A Source

HP E5500  Carrier 2.4E+9 Hz  25 Jul 1997  10:56:38 - 10:58:49

L(\text{f}) \ [ \text{dBc / Hz} ] \ \text{vs} \ f \ [ \text{Hz} ]
AM Noise Measurements

NOISE SIDEBANDS MAY NOT BE ENTIRELY PHASE
AM Noise Measurements

Noise sidebands may not be entirely phase
AM Noise Measurements

Noise Sidebands May Not Be Entirely Phase

Agilent E5500 AM Noise Measurement (8644B)


M(f) [dBc/Hz] vs f [Hz]

10  100  1K  10K  100K  1M  10M  100M
Pulsed Phase Noise on signal

Phase Noise is superimposed on every spectral component

- Max phase noise measurement offset is PRF/2
- PRF lines dominate the phase noise plot > PRF
- AM detector for AM measurements see all the Power

\[ f_c \]

\[ \frac{PRF}{2} \]
Pulsed Phase Noise Measurements past PRF/2
Keysight E5500 Phase Noise Measurement System

GOLD STANDARD PHASE DETECTOR-BASED SYSTEM

• Can configure E5500 system as:
  • Reference-source/PLL system
  • Frequency-discriminator system
  • Solution for absolute & residual phase noise measurements
  • Solution for pulsed phase noise measurements
• System is complex, but offers most measurement flexibility & best overall system performance
• Can use any frequency-tunable reference sources for best possible absolute phase noise measurements
N5511A Phase Noise Test System (PNTS)

INDUSTRY LEADING REPLACEMENT FOR E5500 PHASE NOISE TEST SYSTEM

“See Farther Down in Phase Noise”

• Best-in-Class Absolute and Residual Measurements
  • Measure down to $kT$ thermal phase noise floor: $-177\text{dBm/Hz}$
  • Extremely fast and flexible for the most demanding measurements
  • Phase detector method for best dynamic range (by canceling the carrier)
  • Multi-Segment cross-correlation in FPGA Hardware
  • Ability to add external splitters, attenuators, amplifiers, and other test setup independently to each channel accessories and suppress any additive noise from these devices via the cross-correlation process

• Completely code compatible with the E5500A
• “Future Proof” with PXIe

Coming…
…June 2019
PNTS Residual Measurement with DUT

Residual Phase Noise Measurement

- Marker Frequency
  - 1: 100.96 Hz
  - 2: 989.48 Hz
  - 3: 10.014 E+3 Hz
  - 4: 100.71 E+3 Hz
  - 5: 1.001 E+6 Hz
  - 6: 9.9121 E+6 Hz

- Amplitude
  - 1: -145.38 dBc/Hz
  - 2: -156.18 dBc/Hz
  - 3: -162.65 dBc/Hz
  - 4: -167.9 dBc/Hz
  - 5: -172.93 dBc/Hz
  - 6: -174.06 dBc/Hz

L(f) [dBc/Hz] vs f [Hz]
Summary of Techniques

Spectrum/signal analysis with quick checking of phase noise
- Non-drifty signal sources
- Phase-locked VCOs
- Signal sources with low AM noise
- PN on CW carriers
- Offset from 100 Hz to 10 MHz
- Spot frequency (PN/carrier drift vs. time)

Phase noise with other frequency, power, spectrum measurements
- VCOs
- SAW oscillators/crystal oscillators
- DROs
- PLL synthesizers
- Drifty signal sources
- Transmitters
- Clock generators
- PN on CW carriers
- Very low PN @ far-out offset
- Offset from 1 Hz to 100 MHz
- Frequency, phase, and power transient over time
- AM noise
- Spectrum monitor
- Frequency, RF power, and DC current
- Baseband noise

Dedicated phase noise measurements
- VCOs
- DROs
- Crystal oscillators
- Synthesizers
- Amplifiers
- Converters
- PN on CW and pulsed carriers
- Extremely low PN over wide offset
- Offset from 0.01 Hz to 100 MHz
- Absolute PN
- Residual noise
- AM noise
- Low-level spurious

160MHz
The Infiniium UXR-Series

MORE ACCURATE ANALYSIS - RUNS FASTER - FULLY UPGRADABLE

- Models from 13 GHz to 110 GHz of real-time bandwidth
- 2 or 4 channels per scope - ALL with FULL rated bandwidth
- Best in class sample rates:
  - 13 – 33 GHz 3.5 mm models: 128 GSa/s per channel
  - 25 – 110 GHz 1 mm & 1.85 mm models: 256 GSa/s per channel
- 200 Mpts/ch standard – Upgradable to 2 Gpts per channel
- High-Definition 10-bit Analog-to-Digital Converter (ADC)
- Best signal integrity and vertical resolution
- Hardware based acceleration ASICs
- Optional self calibration module – enables you to perform a factory quality frame calibration at your location
Jitter Analysis
Phase Noise Application – Now Supported with the UXR

WHY MEASURE PHASE NOISE WITH A SCOPE?

• As clocking requirements get tighter, phase noise measurements supplement traditional jitter measurements

• mmWave applications require the ability to measure low phase noise at high frequencies

• Ability to measure phase noise on a variety of signals (square waves differential, probed signals, with SSC…)
Importance of Calibration
References


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