Source Impedance Influence on Cross-Correlation Phase Noise Measurements

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Abstract—The phase noise floor of an oscillator has been shown both theoretically and experimentally to be the ratio of the source noise power divided by the delivered power. In a 50Ω system this is determined by \(-177\,\text{dBm} - P_{\text{out}}\) in dBC/Hz. Recent measurements have shown what appears to be better than theoretical noise floors in some oscillators, assuming a 50Ω environment. However, oscillators rarely exhibit an output impedance of exactly 50Ω and vary significantly farther from the carrier. While the input impedance of a modern cross correlation analyzer may be 50Ω, the assumption the analyzer introduces 50Ω common mode noise can be erroneous. This paper presents theory and measurements that demonstrate the extremely low phase noise measured on some oscillators is real and not in violation of theoretical limits by isolating the noise sources in a series of additive phase noise measurements.

Keywords—phase noise; additive; residual; noise; noise-floor cross-correlation.

I. INTRODUCTION

Leeson's model of an oscillator includes a term for the impedance of the system, usually set to 50Ω, and based on the assumed architecture of the oscillator, is often very accurate for predicting the performance of an oscillator [1]. This model assumes the output power of an oscillator is delivered from the output of the amplifier in the system and includes the noise due to the amplifier and the loop impedance. An alternative to this architecture is the block diagram of an oscillator in Fig 1. The output power is pulled prior to the amplifier and after the resonator. In an inductively coupled parallel resonator, such as a cavity, the impedance of the resonator far from the -3dB bandwidth can be a very low impedance. Regardless of the input impedance of the amplifier, the output noise source impedance far from the carrier will dominated by the resonator impedance past the -3dB point.

![Fig. 1. Oscillator diagram where output impedance and noise is dominated by the output impedance of the resonator, assuming the resonator has a low impedance.](image)

A second architecture that Leeson's formula does not account for is shown in Fig. 2. This architecture adds a clean-up loop to a traditional oscillator. Again, the cleanup loop can be a resonator with a near short circuit far from the -3dB point. Since an oscillator is fundamentally just filtered noise from a positive feedback circuit, this additional loop will filter the noise induced by the amplifier in feedback. The source impedance of Fig. 2 is similar to Fig. 1 where far from the -3dB point it may be a very low impedance. In both of these systems, the measurement of delivered power is still in a 50Ω environment while far from the carrier the noise power is in an entirely different impedance. This discrepancy will result in phase noise levels, far from the carrier, that will be lower than what is possible in a theoretical 50Ω environment.

![Fig. 2. Oscillator diagram where output impedance and noise is dominated by a resonator clean-up loop.](image)

The fundamental question if the above is true is two-fold. First, can a cross correlation phase noise measurement truly differentiate between different sources of noise, itself and the source. Second, can a cross correlation system measure phase noise far from the carrier in which the noise source impedance is something other than 50Ω. Presented below are two measurement setups. First at baseband to demonstrate the ability of the baseband portion of measurement system to identify only noise that is common, regardless of impedance. Cross-correlation systems have shown to measure far below that of either individual channel [2-4]. Second, three additive phase noise measurements are shown in which the noise source is common to all three inputs at two different impedances and one where a 50Ω noise source is added to the common path as a verification. This verification is to provide a reference from [5] in which -177dBm has been determined to be thermal noise floor in a 50Ω environment.
II. BASEBAND CROSS-CORRELATION

To demonstrate the cross correlation measurement and the ability to cancel noise that is common only between the two channels, regardless of the impedance of either channel, a simple test setup is shown in Fig 3.

The first test identifies the capability of the cross correlation system to show truly independent noise paths. In Fig. 4, the first (blue) and second trace (red) shows the measurement from Fig. 3c and Fig. 3b, respectively, as a single channel. The third trace (red) and fourth traces (black) are the cross correlation results from Fig 3c and Fig 3b, respectively. This measurement demonstrates that any noise introduced in either channel uniquely, but not common, will be correlated out of the measurement. The fourth trace (black) in Fig. 4 is from the setup in Fig 3a, demonstrating the isolation of the measurement. A setup similar to this was originally used to calibrate the cross correlation measurement system in [6].

The second test results are shown in Fig. 5 using the setup in Fig3c. The series 50Ω resistor into each path emulate a resistive spliter that can be used to split a signal without introducing common mode noise. The measurements in Fig. 5 demonstrate the near theoretical results for each resistor value inserted. In each case, the results are within 0.1dB of the theoretical noise values.

III. CROSS-CORRELATION AT RF FREQUENCIES

A. Measurement Setup

Cross-correlation at RF frequencies accomplished two identical discriminators, each with their own unique noise source. A Holzworth HA7402B cross-correlation engine was used for these measurements. The input circuits were optimized for 0-5dBm levels to ease the measurement time. The important aspect of the HA7402B is the >100dB port-port isolation of each of the three ports at 100MHz. Port match is better than -30dB. A good cross-correlation measurement system is designed to not introduce any common mode noise into the DUT path while maintaining very high port to port isolation. In mixer only systems port isolation may only be 20-40dB, causing feedthrough and corrupting the measurements at these levels.

The source is a Wenzel Onyx series 100MHz OCXO with very good close to the carrier phase noise and a -175dBc/Hz floor. The output of the OCXO was buffered by attenuators and a Holzworth HX2400 amplifier. Careful attention was paid to isolate the OCXO from the measurements so as not to introduce any potential injection locking or pulling.
To identify that the cross correlation system only measures noise unique to the common path, regardless of output impedance of the source, a setup was built shown in Fig. 6 using two different types of power dividers. One divider is resistive only at the input, providing a low impedance direct connection to all three paths while providing a 50Ω port match at the input. The output impedance is 12.5Ω. The second is a more traditional three-way Wilkinson power divider. The schematic level of these dividers is shown in Fig. 10. This experiment identifies whether the cross-correlation engine with two discriminator paths can cancel noise due to the source, regardless of impedance. It adds a secondary result on whether a divider introduces a unique noise component to each path or is common to all and therefore cancelled.

B. Measurement Results

The measurement results of the two splitters are shown in Fig. 7. The measurements were stopped at 200 correlations for reasons of measurement time. After 200 correlations the measured floor was -186dBc/Hz for both power dividers and still relatively uncorrelated. At 5dBm input power and a 50Ω noise source system, the measurement noise floor would be -182dBc/Hz. What this measurement demonstrated was the noise was common between all three ports. This is easy to see for the resistive splitter but more difficult for the Wilkinson, both shown schematically in Fig. 10. Two different source impedances were used to show that the source noise is cancelled out (similar to the noise around the carrier) regardless of impedance. The additive measurement will only measure noise added by the common path, regardless of impedance.

The verify that the correct floor is measured, assuming a 50Ω noise source environment unique to the DUT path, the setup in Fig. 8. was built to provide 0dBm into the HA7402B while maintaining 5dBm LO drive levels. To introduce 50Ω noise that is common only to the DUT path, a 12dB attenuator was used. The pi-attenuator topology introduces near 50Ω noise, incoherent with the other two channels. The measurement results are shown in Fig. 9. A level of -177dBc/Hz was measured, as predicted by theory.
Fig. 10. Schematic representations of the two power dividers used in the cross-correlation measurements. Both split the signal equally with the resistive splitter port matched at the input with low output impedance. The Wilkinson is band limited but provides additional isolation. The noise in both cases is entirely common to all three paths, being cancelled out in the discriminator. The resistors in the star-topology Wilkinson add noise, but add it in common to all three channels.

C. Power Dividers as Noise Sources

Two drastically different power dividers were chosen. The first is resistive only. This changes the output impedance of the splitter to be 12.5Ω with the noise component being common by a direct connection. This was done deliberately to isolate the power divider from the noise source. The results are conclusive in that the cross-correlation engine, far from the carrier, is not adding 50Ω noise to the system.

The second splitter is the Wilkinson. Given it’s output impedance is 50Ω, it is not immediately clear that the noise source is common between all ports. Measurement results indicate that the noise component is transposed back to the input of the divider, becoming common mode. The cross-coupled nature of the resistors in the Wilkinson also cross-couple the noise. This results in the noise becoming common and is input referred. This also demonstrates that a Wilkinson divider, as the front end of a cross-correlation measurement setup, may actually introduce 50Ω noise, as it could input refer the resistor noise, which would be common in the DUT path.

This is a significant result as potentially all cross-correlation engines will have a similar front end as HA7402B and some may actually introduce noise in that path, limiting the dynamic range of the measurement. The HA7402B uses a broadband resistive splitter shown to not introduce common mode noise in the first series of baseband measurements.

IV. CONCLUSIONS

The impetus behind these series of measurements were to try to prove that source phase noise can be below that of the theoretical -177dBm/Hz - P_{out} levels of a 50Ω system, provided the output impedance is sufficiently low. The question is whether a cross correlation system could correctly measure a signal source noise that is below the 50Ω input impedance of the analyzer.

Based on the measurement results it can be concluded that the cross correlation measurement system has the ability to measure signals with a source noise impedance lower than 50Ω. A measurement can be taken (assuming enough correlations and time) that would show an oscillator could have better than the 50Ω assumed -177dBm/Hz - P_{out} provided the source impedance of the oscillator was sufficiently low and no other significant noise source was introduced after the oscillator. The power dividers at the input of the HA7402B analyzer do an effective job of isolating the noise channel to channel while not introducing 50Ω noise but maintaining a matched port impedance.

As a side note, modern simulators often include all noise sources in the system, including the noise due to a 50Ω termination. It may be unclear how this may affect the predicted noise floor. The cross-correlation engine is designed specifically to isolate only the oscillator and not include the presence of this noise. Therefore, simulator predicted noise floors may be different than actual measurements due to the uncertainty in the simulated noise sources.

The additive cross-correlation phase noise measurement technique was applied to test this theory to help isolate any form of injection locking or inadvertent non-linearity when using multiple oscillators. To add more proof to the basis of this work an additional measurement may be taken in which a very low noise oscillator is followed by a very high-Q cavity filter with an effective short circuit beyond the -3dB point. The author expects that a measurement floor below -177dBm - P_{out} will be observed based on the measurements provided in this paper.

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REFERENCES