Use of Induced Noise to Calibrate Injection-Locked Phase Noise Measurements

Alberto Rodriguez, *Student Member, IEEE*, Lawrence P. Dunleavy, *Senior Member, IEEE*, and Ali Boudiaf, *Senior Member, IEEE*

***Abstract*—A new calibration approach is described for phase noise measurements of free-running voltage controlled oscillators using the injection locking technique. The injection locking technique allows the locking of free running oscillators to a reference over a wide bandwidth during a phase noise measurement. Compared to conventional phase noise measurement techniques, the injection locking technique involves a calibration procedure, which may be tedious and time consuming. The new approach may be used to perform an automated calibration procedure of the system commonly used for these measurements.**

***Index Terms*—Injection locking, measurement calibration, phase noise, phase noise measurement.**

I. INTRODUCTION

INJECTION locking is a well-known physical phenomenon in which an oscillator's output frequency will track the frequency of an injected signal within a limited bandwidth. This bandwidth, called the locking bandwidth, is dependent on the quality factor Q of the oscillator and on the magnitude of the injected signal. Once locked to the injected signal, the frequency drift of a free-running oscillator is eliminated. Since the phase noise of a locked oscillator will be suppressed within the locking bandwidth, it is necessary to accurately characterize the locking bandwidth in order to correct for the decreased phase noise levels. As demonstrated by the authors in a recent conference paper [1], it is possible to intentionally induce broadband phase noise as a means to determine the locking bandwidth. Since this novel procedure can be automated, it provides a path to automatic calibration of injection locked phase noise measurement systems.

II. THEORY

A phase noise measurement system employing the injection locking technique is shown in Fig. 1. The locking signal is sampled from the reference source and injected via a directional coupler. Step attenuators are used to adjust the magnitude of the injected signal and thus the range of frequencies to which the oscillator will remain locked. An isolator is included to keep the LO-to-RF leakage at the mixer from unintentionally injection locking the oscillator. The synchronized oscillator signal is phase compared to the reference source at the mixer. The output of the mixer, operated as a phase detector, is proportional to the phase noise of the locked oscillator.

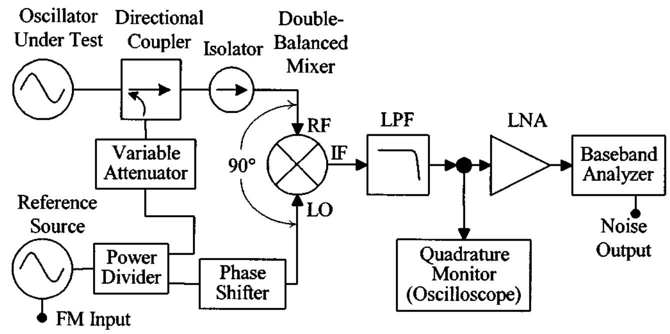

Fig. 1. Block diagram of the basic injection locking measurement setup.

When the oscillator is injected with an external low-level[1] injection signal, the phase dynamics of the injection-locked oscillator are described by the so-called Adler equation [2]:

$$\frac{d\phi}{dt} = -\frac{\omega_{free}}{2Q}\left(\frac{A_{inj}}{A}\right)\sin(\phi) + \Delta\omega_o \quad (1)$$

$$\Delta\omega_o = \omega_{free} - \omega_{inj} \quad (2)$$

$$\phi = \phi_{lock} - \phi_{inj} \quad (3)$$

$$V = Ae^{j\phi_{lock}} \quad (4)$$

$$V_{inj} = A_{inj}\exp j\phi_{inj} \quad (5)$$

where $\phi_{lock}, \omega_{free}, Q$ and V are, respectively, the instantaneous phase of the output signal, free-running frequency, loaded Q factor of the embedding network and the output voltage phasor of the oscillator V_{inj} is the voltage of the injected signal, and A and A_{inj} are the magnitudes of the phasors V and V_{inj}, respectively.

Equation (1) makes it possible to determine the behavior of the oscillator disturbed by a weak external signal. When the voltage-controlled oscillator (VCO) is locked to the injected signal

$$\frac{d\phi}{dt} = 0. \quad (6)$$

The locking condition then becomes

$$\Delta\omega_o = \frac{\omega_{free}}{2Q}\left(\frac{A_{inj}}{A}\right)\sin(\phi), \quad (7)$$

where $\Delta\omega_{\max} = |\Delta\omega_o| = \omega_{free}/2Q\,(A_{inj}/A)$ is the maximum frequency deviation possible for the locking condition.

[1]See [5] for an analysis of large signal injection.

Manuscript received October 12, 2000; revised January 17, 2001. The review of this letter was arranged by Associate Editor Dr. Arvind Sharma.

A. Rodriguez and L. P. Dunleavy are with the Department of Electrical Engineering, University of South Florida, Tampa, FL 33620 USA (e-mail: alrodrig@eng.usf.edu).

A. Boudiaf is with Agilent Technologies, North Billerica, MA 01862 USA.

Publisher Item Identifier S 1531-1309(01)03209-3.

The phase noise of the oscillator in its free-running state is determined from the measured double-sideband power spectral density of the voltage fluctuations $v^2(\omega_m)$ [V^2/Hz] at the IF port of the mixer. The following expression is used [3]:

$$\phi^2 vco(\omega_m) = \frac{4{\omega_m}^2 + {\Delta\omega_{lock}}^2}{{G_P}^2 4{\omega_m}^2} v^2(\omega_m). \tag{8}$$

In (8), ω_m is the offset frequency from the carrier at which the measurement is made, G_P is the phase detector constant of the mixer operated in quadrature, and $\Delta\omega_{lock}$ is the injection locking bandwidth, defined as

$$\Delta\omega_{lock} = 2\Delta\omega_{\max}. \tag{9}$$

The phase detector constant and the locking bandwidth completely characterize the measurement system in Fig. 1.

The phase detector constant and the locking bandwidth are the two measurable parameters needed to perform a calibration of an injection locking measurement system. The phase detector constant can be obtained by measuring the beat signal present at the output of the phase detector when the reference source and the oscillator are offset in frequency [4], or by introducing an FM sideband with known modulation rate and observing the response of the system. The locking bandwidth can be obtained by carefully tuning the injection signal across the center frequency of the oscillator and observing the frequency band in which the oscillator will remain locked to the reference. The accuracy of obtaining the locking bandwidth using this method is limited to the tuning step size of the reference source and operator judgment, since it is very difficult to determine when a locked condition exists at the band edges.

III. New Calibration Technique

Calibration of the injection locking system of Fig. 1 requires characterization of the phase detector constant and the locking bandwidth of the oscillator at a particular injection signal magnitude. With the oscillator-under-test in place, the phase detector constant can be obtained using the conventional methods mentioned above. Once the phase detector constant is known, the oscillator-under-test is injection locked, and the reference source is tuned to the nominal carrier frequency of the oscillator. This procedure ensures that the oscillator is in close proximity to the center of the locking bandwidth [3].

Instead of tuning the reference source to determine the locking bandwidth, the reference is frequency modulated with a broadband random signal, such that the resulting (artificially induced) phase noise of the reference is higher than that of the oscillator being tested. The output spectrum of the system is observed with the oscillator in both the unlocked and locked conditions. For the unlocked case, the spectrum observed at the output of the phase detector is a line with a slope of 20 dB per decade that is similar to the spectrum that is produced by the white noise frequency modulation. A white noise modulating signal is used because of its flat frequency characteristic, which is changed to $1\backslash f^2$ when transformed into phase noise by frequency modulation. Within the locking bandwidth of the system, this same 20 dB per decade line levels off to a flat (zero slope) line. The output spectrum resembles the frequency response of a low-pass filter with a 3 dB roll-off frequency equal to half the injection locking bandwidth. This is shown in Fig. 2.

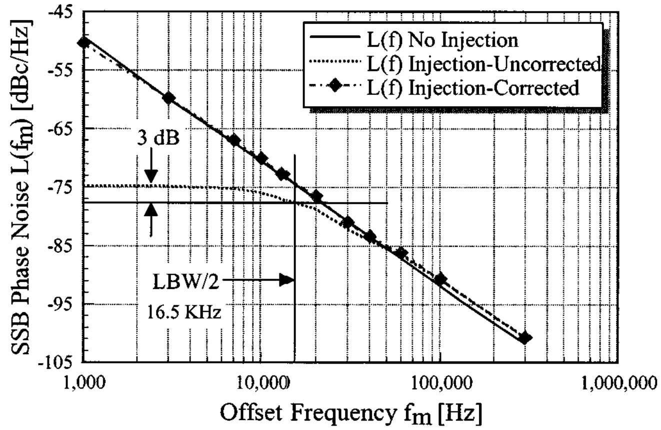

Fig. 2. Example of random noise modulated response for the injection locking system in the unlocked and locked conditions.

For the curve labeled *injection-uncorrected* in Fig. 2, the 3 dB point below the flat region yields a frequency offset equal to half of the injection locking bandwidth, in this case 33 KHz. Using 33 KHz as the locking bandwidth in (8), the data was corrected and shown in Fig. 2 as *injection-corrected*. Note that the corrected data is reasonably close to the curve labeled *no injection*.

The result of this technique is an accurate determination of the locking bandwidth, in an efficient manner that may be automated. This information is used along with the phase detector constant to correct for the phase noise suppression caused by injection locking the unknown oscillator under test.

IV. Measurements and Comparisons

The phase noise measurement system was setup as shown in Fig. 1. The phase detector constant was measured to be 95.1 mV/radian, and the locking bandwidth was estimated at 932 kHz by tuning the reference signal. When determining the locking bandwidth by means of tuning the reference source, errors are introduced by the difficulty in determining the edges of the locking bandwidth, and by oscillator drift while making the measurement. The random noise modulation technique was used and the locking bandwidth was determined to be 992 KHz. Connecting the baseband analyzer noise output to the FM input of the reference source (HP8672A) generated the random noise modulation.

To enable a comparison, the phase noise of the free-running oscillator was calculated using (1) and the locking bandwidths obtained with both the tuning and the random noise modulation techniques. Fig. 3 compares the results of the phase noise measurements and shows the device specifications. Because the oscillator-under-test is stabilized by injection locking when employing the broadband noise technique, a more accurate determination of the locking bandwidth is possible.

The results obtained using injection locking to measure phase noise were compared to other systems. The purpose of this comparison was to verify the measurement and calibration technique

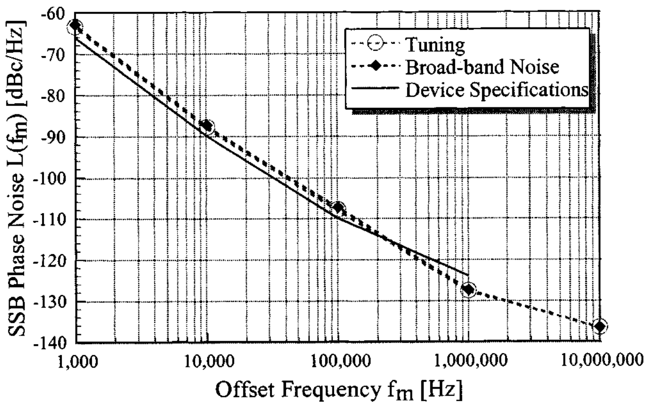

Fig. 3. Comparison of results using both the reference tuning and the random noise modulation techniques for obtaining the locking bandwidth.

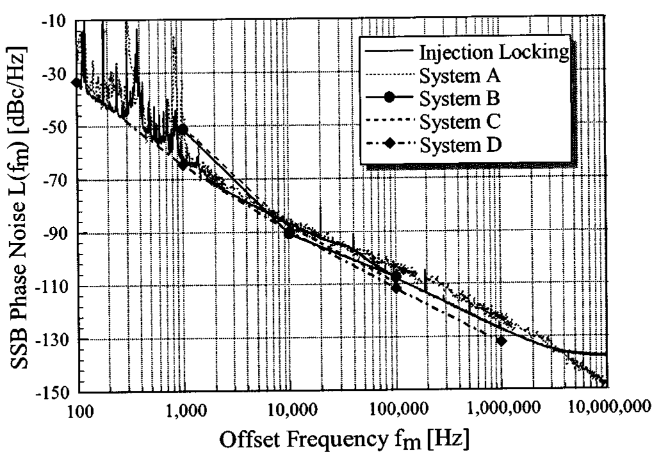

Fig. 4. Measurement results of the injection-locked measurement compared to several commercial systems.

presented against commercial systems, all measuring the same free running VCO unit. The results presented in Fig. 4 validate the accuracy of the injection locking technique calibrated using broadband noise. To avoid competition related issues, the systems used are not specified. These commercial systems employ different techniques to measure phase noise, including the phase detector and discriminator methods. Differences in the data may be attributed to environmental and operator variations among other measurement factors.

V. Conclusion

A technique for obtaining the locking bandwidth of an injection locking phase noise measurement system has been presented. Using white-noise modulation, the reduction of phase noise caused by injection locking may be accurately characterized. The experimental results show close agreement between measurements made using both the reference tuning and white noise calibration methods. It has been shown that the white noise modulation technique is an accurate method for determining the locking bandwidth of an injection locked oscillator. Additionally, this method is suitable for automating the calibration procedure for the injection locking technique.

Acknowledgment

The authors would like to thank M. Wyatt of Xetron, formerly of Honeywell, Inc., L. Miller of Xetron, formerly of Trak Microwave, and D. Gamliel of Mini-Circuits for their various inputs on this work.

References

[1] A. Rodriguez, A. Boudiaf, and L. P. Dunleavy, "Calibration of injection-locked phase noise measurements," in *53rd Automatic RF Techniques Group Conf. Dig.*, Anaheim, CA, June 1999.
[2] R. Adler, "A study of locking phenomena in oscillators," *Proc. IRE*, vol. 34, pp. 351–357, 1946.
[3] X. Zhang, B. Rizzi, and J. Kramer, "A new measurement approach for phase noise at close-in frequencies of free-running oscillators," *IEEE Trans. Microwave Theory Tech.*, vol. 44, pp. 2711–2717, Dec. 1996.
[4] Hewlett-Packard Staff, "Phase noise characterization of microwave oscillators: Phase detector method,", Product Note 11 729B-1, March 1984.
[5] E. F. Calandra and A. M. Sommariva, "Approach to the analysis of non-linear feedback oscillators under large-signal injection," *Proc. Inst Elect. Eng. G*, vol. 133, pp. 233–241, Oct. 1986.