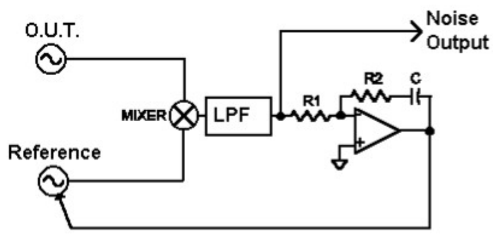
Low-Cost Phase Noise Measurement

Low noise crystal oscillators can exhibit exceptionally low close-in phase noise which cannot be directly measured with a spectrum analyzer or frequency discriminator. The most common measurement technique compares the phase of an oscillator under test to a reference oscillator with similar or superior noise performance. An ordinary PLL can make the measurement easier by holding the relative phase of the two oscillators at quadrature which is usually the best point for converting small phase variations into voltage variations. Although the PLL is constantly working to eliminate these phase variations, the time constant can be set long enough to preserve the slowest phase variations of interest. A typical block diagram is shown below where the oscillator under test and a reference oscillator are directly connected to a double-balanced diode mixer. The mixer output is connected through a low pass filter to block the RF frequencies to a phase lock amplifier. The resistors and capacitor are selected to give a loop bandwidth well below the lowest frequency to be measured. The phase slope is volts per radian and the tuning sensitivity is radians per second - volt which is 2 pi Hz per volt.. (See: useful spreadsheets)



$$\omega = \sqrt{\frac{k_\phi k_v}{R1\ C}} \qquad \zeta = \omega \frac{R_2 C}{2}$$

k_ϕ = phase slope

k_v = tuning sensitivity

The low pass filter should remove radio frequencies but it shouldn't have a roll-off frequency near the loop bandwidth or else the loop may become unstable and it should be wide band enough to let the noise through at the highest frequency of interest. The noise output is typically sent to a low noise amplifier followed by an audio spectrum analyzer, wave analyzer, or filter. A low noise amplifier may not be necessary if the analyzer noise floor is sufficiently low.

Complications

The above scheme is simple in appearance but there are a number of choices, complications and pitfalls.

- First, the mixer converts phase variations into voltage variations with a conversion sensitivity that must be determined.
  - One way to determine the conversion factor is to disconnect the electrical tuning and adjust the oscillator frequencies until a beat note can be observed at the output of the mixer using an oscilloscope. The slope of the zero-crossing can be determined in volts per radian keeping in mind that one full beat note corresponds to 2 pi radians. Pitfalls: The amplifiers connected to the PLL may be overdriven by the beat note and cause a measurement error. If they are disconnected, then the loading of the mixer changes which may change the phase slope, especially if a low impedance load is not used at the mixer output (for better phase slope). An amplifier that can be switched to a lower gain without changing its input characteristics is useful. Also, the positive and negative phase slopes may be different and it becomes necessary to determine which slope is used when the loop is locked. Different positive and negative slopes can indicate "injection locking" caused by insufficient oscillator isolation. Buffer amplifiers or even frequency multipliers will usually reduce or eliminate injection locking. The phase slope is being checked at only one frequency and there may be a non-flat frequency response, especially if an unusual mixer circuit is used to enhance the phase slope. When only close-in noise is to be measured or the noise floor is not pushing the limits of the measurement, it is a good idea to terminate the mixer output with 50 ohms.
  - Another technique for determining the slope is to carefully determine the sensitivity of the electrical tuning of one of the oscillators and apply an audio signal to generate a precise frequency modulation. The oscillator's electrical tuning network must have sufficient bandwidth to not roll off the modulation signal and tuning non-linearity must be considered if the DC point is moved. It may be advantageous to connect the PLL tuning voltage to the O.U.T. so that the modulation may be applied to the reference oscillator electrical tuning with a fixed DC bias. To measure the slope, lock the PLL and apply a small audio tone at a low frequency (well within the tuning bandwidth of the oscillator) and small enough to not overdrive the low noise amplifier. The resulting radian modulation level is calculated from Xrad = Vmod (volts) x Tuning Sensitivity (Hz/volt) / Tone Frequency (Hz). Measure the signal height on the analyzer and the ratio of this measurement to the calculated radian value is the phase slope. Some analyzers use a variable measurement bandwidth and then normalize the noise measurement for 1 Hz. Remember to turn off this bandwidth normalization (volts per root-Hz) when measuring the phase slope or other non-random signals. You can also measure the calibration modulation using an oscilloscope connected to the output of the low noise amplifier.
- Noise contributed by the PLL can cover the oscillator's noise. Use lower value resistors and a low noise op-amp.
- A low damping factor in the PLL can give a noise "bump" which exaggerates the noise near the loop bandwidth frequency.
- Large signals, line related frequencies and large amplitude low frequency noise can cause amplifier overload which will cause false readings.
- Audio noise on the grounds can get into the low noise audio amplifier and cause false high readings. Shunt oven currents and other power supply currents directly back to the power source instead of through the signal coax when possible.

The simplified procedure for measuring the phase noise follows:

- Measure the phase slope.
- Connect the electrical tuning and PLL and low noise amplifier. Readjust the oscillator frequency to achieve lock with the tuning voltage near the middle of the tuning range. The LPF output should be near zero volts.
- Measure the audio spectrum at the output of the low noise amplifier.

Here is an example of a typical measurement and the required calculations:

Suppose a wave analyzer with a 9 Hz bandwidth measures 17 uVrms at 1 kHz and the mixer has a phase slope of 0.8 volts/radian. Also assume that the low noise amplifier has a gain of 60 dB. First, divide 17 uV by 0.8 volts/radian to convert the voltage into radians. Now divide by the square-root of the measurement bandwidth (sqrt(9) = 3) to normalize to 1 Hz bandwidth. Now calculate the log (base 10) and multiply by 20. Subtract the amplifier gain (60dB), subtract 3 dB if you are assuming the oscillators contribute equal noise to the measurement, and subtract 3 dB to correct for the fact that the measurement is actually double-sideband:

L(f) = 20log(17 x 10-6/(0.8 x 3))-60-3-3 = -169 dBc.

Measuring the phase slope using the beat note technique:

Disconnect the electrical tuning and the low noise amplifier. Connect an oscilloscope to the LPF output. The scope input and trigger should be DC coupled! Detune one oscillator until one full cycle fills the screen with a fairly slow sweep speed. Increase the sweep speed by an exact factor of 100. The full screen is now 0.02 pi radians. Adjust the trigger (not the vertical position!) to measure the slope of the trace as it crosses zero volts. If the trace is curved then try to estimate the line that best fits the curve at the zero crossing. For example, if the trace (or best straight line) spans 50 mV then the phase slope is .05/.02 pi = 0.8 volt/radian

---

Circuits

Audio Amplifier: It is fairly easy to build an excellent low noise audio amplifier with ordinary op-amps. Many amplifiers are available with noise voltage below 5 nV per root-Hz and a few exhibit noise below 1 nV. It is useful to have the choice of AC or DC coupling and perhaps two gain settings. Use low value, low noise resistors for gain setting. The technical library has an unusual amplifier circuit featuring low noise junction FETs. This circuit provides 60 dB of AC-coupled gain with three high-pass settings, a DC-coupled 30 dB setting and a 0 dB gain setting for measuring phase slope. The phase lock amplifier includes a slew switch to speed phase locking. The PLL input and the output are buffered. A new Blue Top audio amplifier module (LNAA) is now available featuring noise below 1 nV/root-Hz and gain from 30 to 60 dB. The bandwidth is over 2 MHz at 30 dB gain. The module has a high current output buffer and an optional 50 ohm input termination. This module is new and a data sheet is in preparation.

PLL: The phase-lock amplifier can be an ordinary op-amp in most applications. The amplifier schematic linked above includes a PLL amp. A complete PLL including the phase detector, filter, lock amplifier and voltage regulator is available in a Blue Top module (LNPLL).

Mixer, Filter: The best choice of mixer for phase noise measurement is the ordinary double-balanced diode mixer. The filter that follows the mixer is not particularly critical since the RF signals to be blocked are usually much higher in frequency than the highest phase noise frequency of interest. Suitable Mixers and filters are available from the Blue Tops line.

A commercial phase noise measurement system is another option. Systems are available ranging in price from a few thousand to nearly one hundred thousand dollars and the vendors range from few-person companies to the largest equipment manufacturers.

[navigate.html]

A Low Noise Amplifier for Phase Noise Measurements

Charles Wenzel

The phase noise of low noise oscillators and signal sources is usually determined by measuring the audio noise voltage at the output of the phase comparator in a phase-locked loop. The phase comparator is typically a low noise doubly-balanced mixer with a phase slope from a few tenths of a volt per radian to a few volts per radian. The low conversion gain of this type of phase detector yields a signal in the low nanovolt per root-hertz range for very low noise sources which is a level below the noise floor of most spectrum analyzers. Suitable low noise preamplifiers are readily constructed from discrete components or from modern low-noise op-amps.

Except for the noise voltage, the amplifier requirements are not particularly demanding. Since the output impedance of the phase detector is low, the input impedance of most amplifier circuits is adequate. A frequency response from a few hertz to 100kHz is usually adequate and the output load is usually a high impedance spectrum analyzer and oscilloscope. The phase detector output impedance is quite low so the noise current of ordinary bipolar transistors is sufficiently low. For example, an ordinary 2N4403 transistor exhibits a noise voltage below 1 nanovolt at 10 Hz when the source is a typical Schottky diode mixer. Several op-amps are available with noise voltages below 3 nanovolts and a few are available with noise voltage below 1 nanovolt. Simple amplifiers built from any of these parts will perform well in most applications. Bulk-metal, wirewound, and metal film resistors exhibit little excess noise and should be used instead of carbon film or carbon composition types. Most potentiometers should be avoided since film and cermet types are quite noisy.

Although the amplifier requirements are minimal, there are several features which may be added to enhance the measurement system. The phase slope of the phase detector is often measured by observing the beat-note of the free-running oscillators. Most simple amplifier circuits will distort this beat-note when they overload so they must be disconnected when checking the phase slope. In some instances, the question of whether reconnecting the amplifier changes the phase slope will arise. For example, the normal low impedance termination used at the output of the phase detector may be left out to achieve a higher phase slope but such an unterminated phase detector can be sensitive to changes in the output load. An adjustable gain amplifier which remains connected to the input avoids the problem. The gain of the amplifier is set to unity for measuring the phase slope then switched to high gain for making the measurement.

Another desirable feature is an adjustable low frequency rolloff. The amplifier should be capable of DC response and two or three AC high-pass selections are helpful. The DC response allows very close-in phase noise measurements and the AC responses allow high gain measurements of the noise floor even in the presence high level close-in noise. A fairly high frequency high pass response is also useful when observing “jumpy” oscillators on an oscilloscope. A high-pass rolloff at 2.5 Hz is also recommended since many phase noise measurements only extend down to 10 Hz and the high-pass will reduce the “settling time”. The DC gain should be below 40 dB since it is used mainly for close-in noise and excessive gain might result in clipping when measuring noisy oscillators. (Alternately, the phase slope of the detector may be reduced by attenuating one of the phase detector inputs but a simple gain switch on the amplifier is more convenient.)

The amplifier should have some RF filtering at the input so that the carrier and sum frequencies from the phase detector do not reach the gain stages. A simple L-C filter with a resonant frequency well above the amplifier’s frequency response and well below the measured oscillator’s frequency is usually adequate. More complex filtering will be necessary if the amplifier’s response must approach the frequency of the oscillators. For example, measuring the phase noise of 1 MHz oscillators out to 100 kHz might require a special filter to prevent the amplifier from overloading. Specific frequency traps may be placed across the amplifier to reduce particular frequencies.

Another convenience is a unity-gain buffer amplifier between the phase detector and the PLL amplifier. This buffer prevents the PLL circuit from disturbing the phase slope measurement due to PLL amplifier overload. A high-impedance buffer also prevents the PLL circuit elements from limiting the utility of the low noise amplifier. For example, the amplifier may be used to measure the audio noise in a prototype circuit but a low resistance PLL input resistor might excessively load the point to be measured.

Fig. 1 shows a complete ultra-low noise amplifier with the features described above. The input circuit includes two 2SK369 JFETs connected in parallel to achieve a remarkably low noise voltage. These surprisingly low noise transistors exhibit a noise floor near 0.7 nanovolts with the noise rising to only 1.5 nanovolts at 10 Hz. The JFETs and the LM833 first stage give a DC-coupled gain of 30 dB. Oscillators exhibiting enough noise to cause this stage to clip are quite noisy and may be measured with the gain set to 0 dB! A second 30 dB amplifier is included for the AC-coupled settings giving a total AC gain of 60 dB. Three AC frequency responses are selected by a multi-pole switch. A buffer drives two BNC connectors, one for a spectrum analyzer and one for an oscilloscope. The PLL is fairly ordinary except that a buffer is provided at the input and a manual "slew" switch is added to speed phase locking. R1, R2 and C1 may be connected with binding posts to allow for easy modifications. A 10k potentiometer may be added across the PLL output to manually adjust the tuning sensitivity for various oscillators.

Only one adjustment must be made to the amplifier circuit. The 2N5639's source resistor must be selected to bring the amplifier's output near zero volts with the input shorted. This FET is a simple current source which sinks just enough current to bring the drains of the 2SK369s down to the voltage on the positive input of the LM833 (set by a resistor divider). Other FETs may be substituted for the 2N5639 as long as the Idss is above about 25 mA.

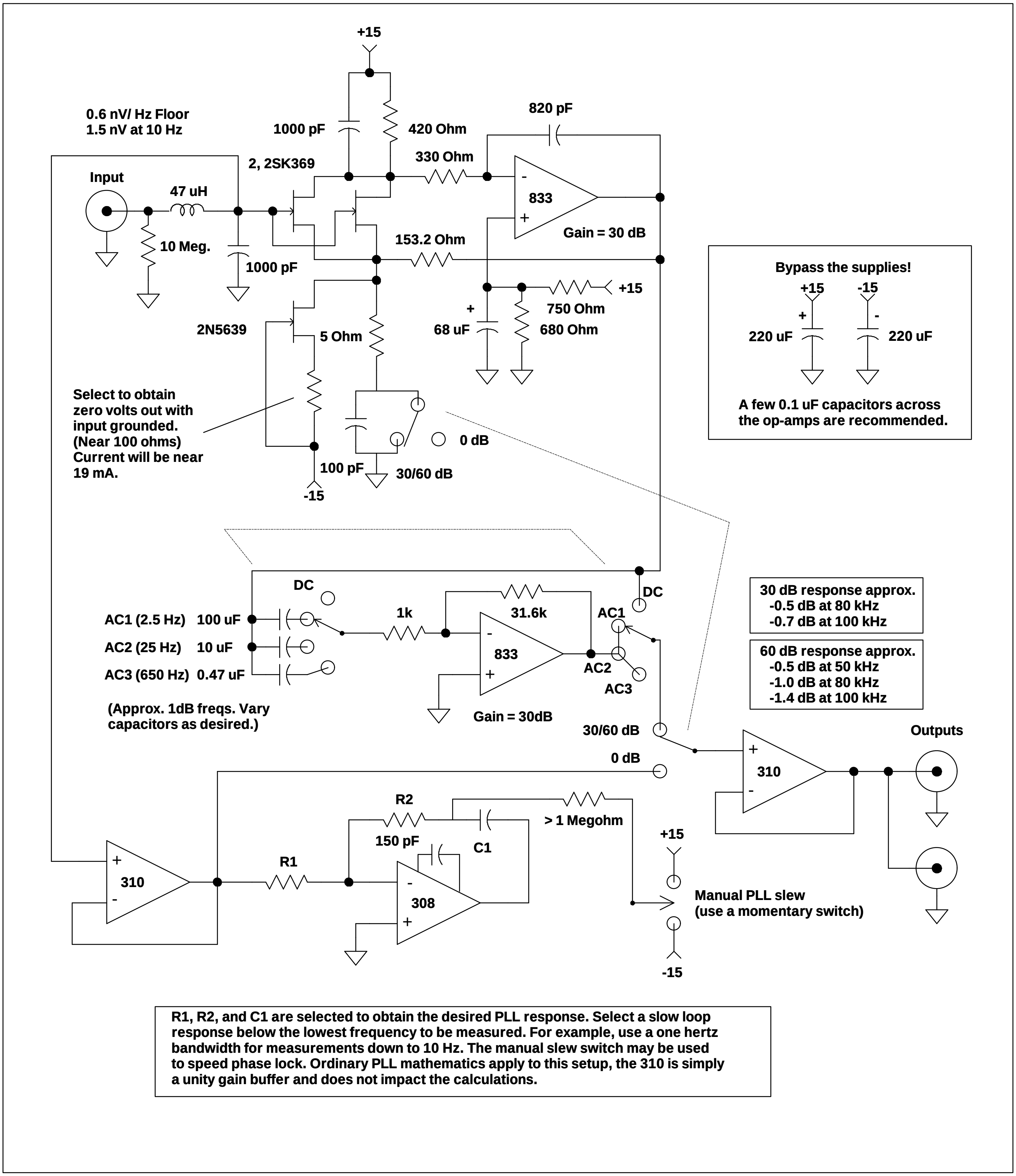


Figure 1: A complete ultra-low noise amplifier and PLL for phase-noise measurements.