A Low Noise Amplifier for Phase Noise Measurements

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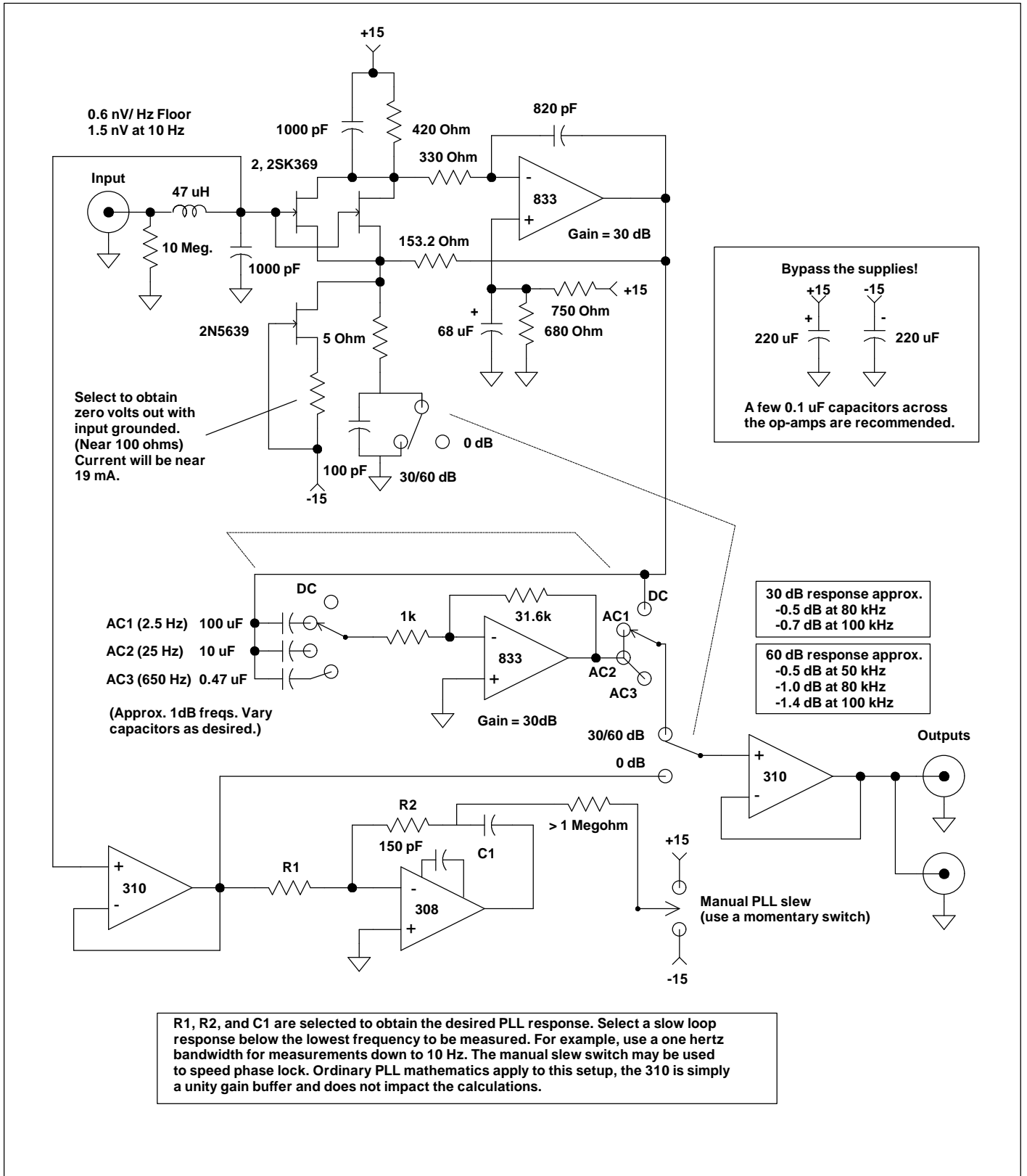
Figure 1: A complete ultra-low noise amplifier and PLL for phase-noise measurements.