Analysis and Measurement of Intrinsic Noise in Op Amp Circuits
Part VI: Noise Measurement Examples
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In Part IV we introduced the different types of equipment used for measuring noise. Now in Part VI, we discuss specifications and modes of operation pertinent to noise measurement. Here we will show real-world examples of how the equipment is used to measure the circuits described in Parts III and IV.

Shielding

When measuring intrinsic noise it is important to eliminate sources of extrinsic noise. Common sources of extrinsic noise are power line pick-up (ie 50 Hz or 60 Hz), monitor noise, switching power supply noise and wireless communication noise. Normally elimination is by keeping the circuit under test in a shielded enclosure, usually made of copper, iron or aluminum; it is important that the shield be connected to system ground.

Generally, power and signal cables are connected to circuits inside via small holes. It is very important that the size and number of these holes be minimized. In fact, shielding effectiveness is less of a concern then leakage through seams, joints and holes.[1]
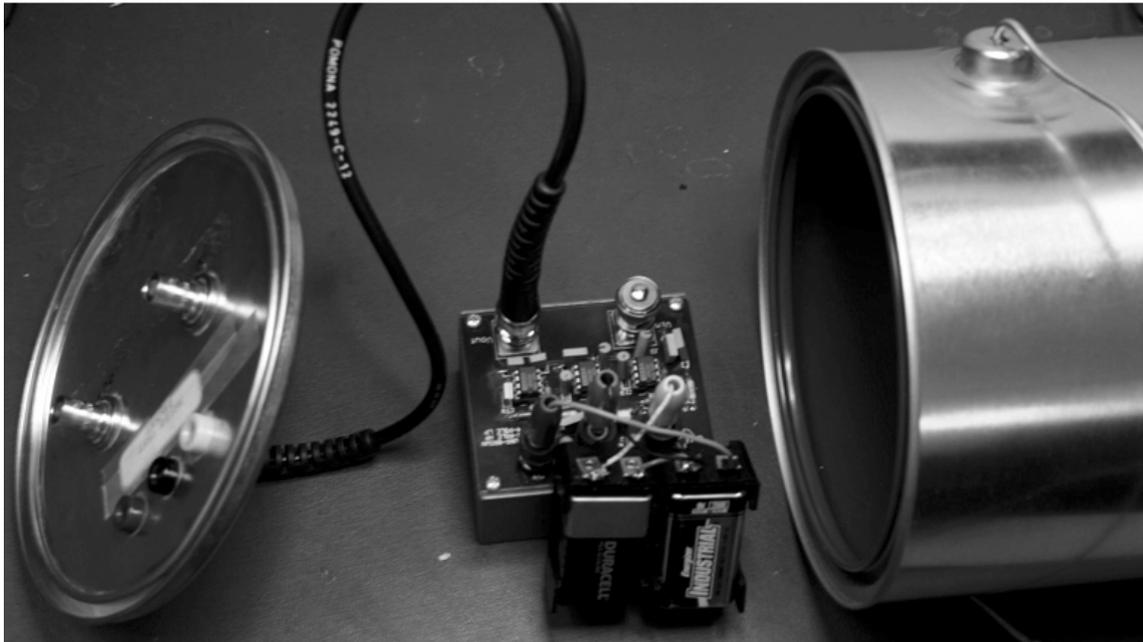

Fig. 6.1: Using a Steel Paint Can

Fig. 6.1 shows an example of an easy-to-build and effective shielded enclosure using a steel paint can (these can be obtained at most hardware stores at nominal cost). The paint can has tight seams and the lid allows easy access to the circuit under test. Note that the I/O signals are connected using shielded coaxial cables. The coaxial cable is connected to the circuit under test using a BNC jack-to-jack connector whose shield is electrically

connected to the paint can. The only leakage path in the enclosure is the three banana connectors used to connect power to the circuit under test. For best shielding, make sure that the paint can lid is tightly sealed. Fig. 6.2 shows a schematic of the paint can test fixture.
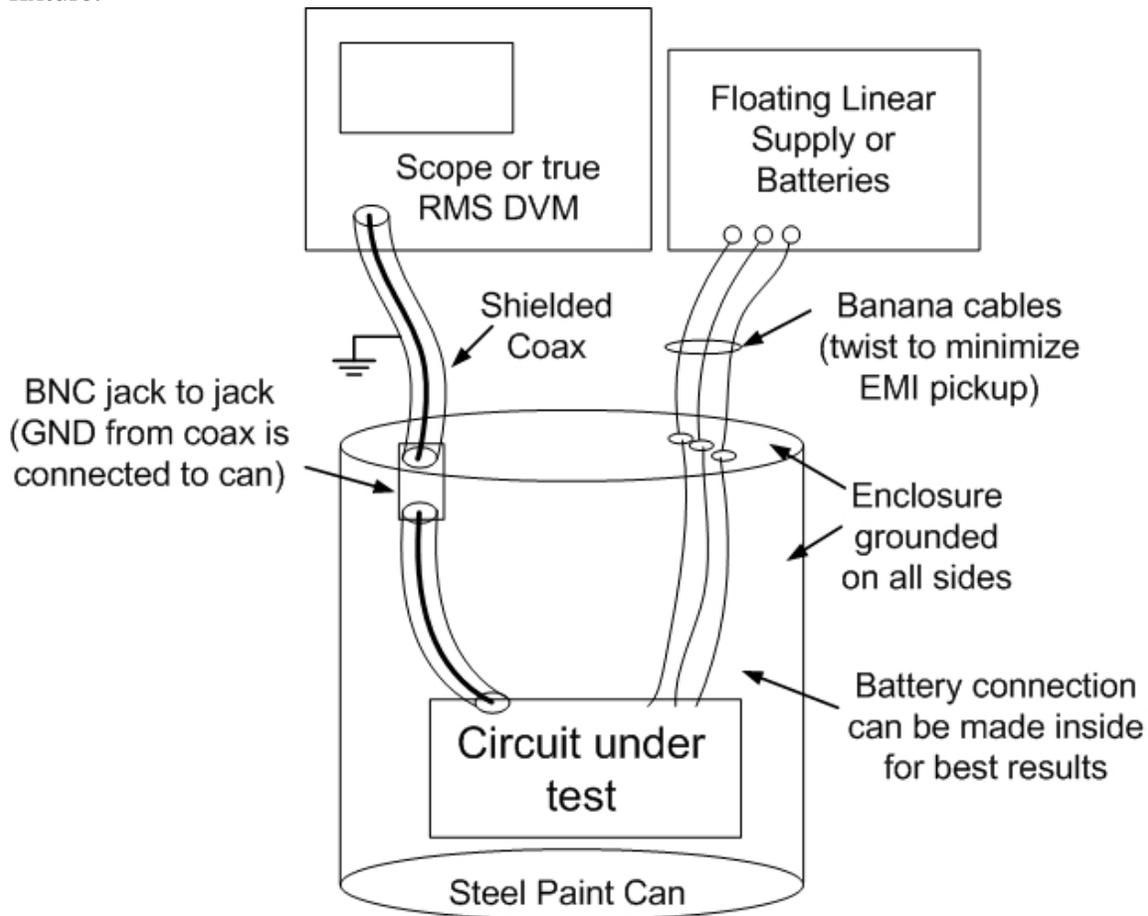

Fig. 6.2: Schematic of Paint Can Test Setup

Verify the Noise Floor

A common noise measurement goal is the output noise of a low noise system or component. It is often the case that circuit output noise is too small for most standard test equipment to measure. Typically, a low noise boost amplifier is connected between the circuit under test and the test equipment (Fig. 6.3). The key to using this configuration is that the boost amplifier noise floor is lower than the circuit output noise under test, so that the noise from the circuit under test dominates. As a general rule of thumb, the boost amplifier noise floor should be three times lower than the noise at the output of the circuit under test. An explanation of the theory behind this rule will be given later. C*hecking the noise floor is an extremely important step that must be performed when making noise measurements.* Typically, the noise floor is measured by shorting the input of the gain block or measurement instrument (see Fig. 6.4). Part V gives details regarding the noise floor measurement on different types of equipment. Failing to check the noise floor often leads to erroneous results.
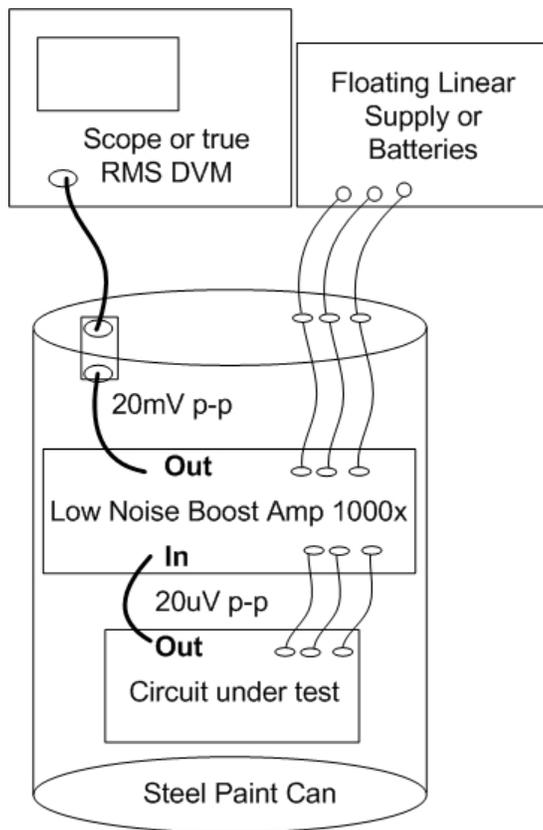
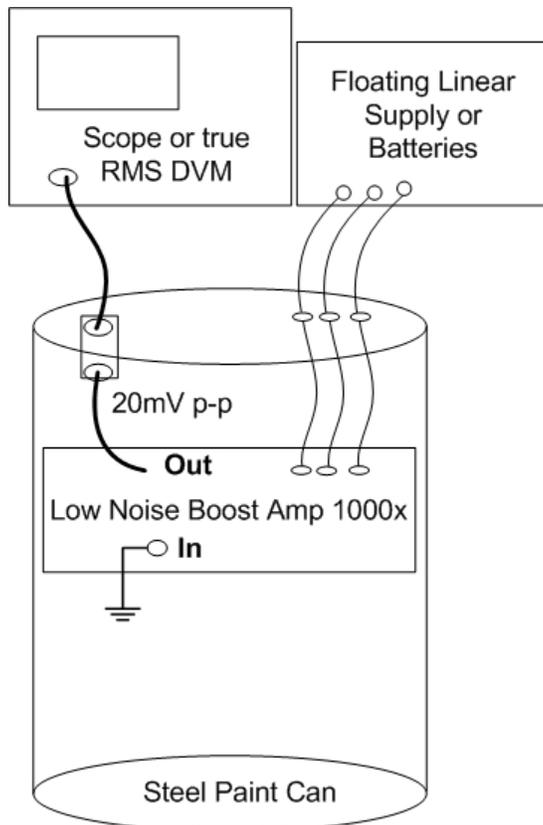**Fig. 6.3: Common Measurement Technique**

Fig. 6.4: Measure Noise Floor

Account for the Noise Floor

For best measurement results, the measurement system noise floor should be negligible in comparison to the noise level being measured. One common rule of thumb is to make sure that the noise floor is at least three times smaller then the noise signal being measured. Fig. 6.5 shows how the noise output of a test circuit and the noise floor add as vectors. Fig. 6.6 shows an error analysis that assumes the measured noise is three times greater then the noise floor. Using this rule of thumb the maximum error is on the order of 6%. If you do the same calculation for a noise floor that is 10x below the measured noise, you get 0.5% error.
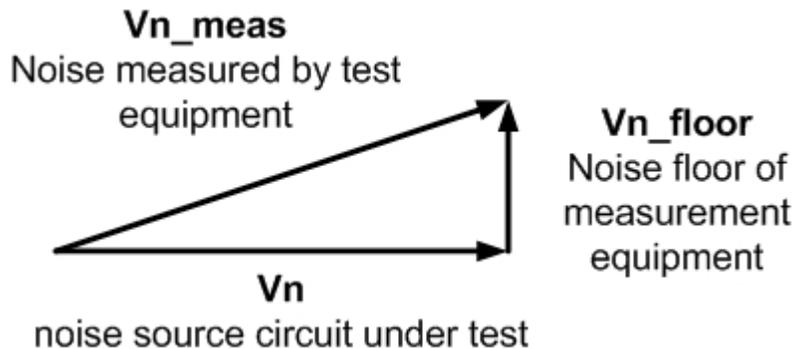

Fig. 6.5: Noise Adds as Vectors

$$V_{n\_meas} = \sqrt{V_n^2 + V_{n\_floor}^2}$$

The measured voltage is the vector sum of the noise from the circuit under test, and the noise floor

$$V_n = \sqrt{V_{n\_meas}^2 - V_{n\_floor}^2}$$

Rearrange the equation to solve for the noise from the circuit under test.

Assuming the noise floor is 3 times smaller then the measured noise What measurement error is introduced by the noise floor?

$V_{n\_meas} = 1$, and $V_{n\_floor} = (1/3)$

$$V_n = \sqrt{V_{n\_meas}^2 - V_{n\_floor}^2} = \sqrt{(1)^2 - \left(\frac{1}{3}\right)^2} = 0.943$$

$$Noise\_floor\_error = \frac{(V_{n\_meas} - V_n)}{V_n} \cdot 100 = \frac{(1 - 0.943)}{0.943} \cdot 100 = 6\%$$

Fig. 6.6: Noise Floor Error in Percent

Measure the OPA627 Example Circuit Using a True Rms Meter

Recall from Parts III and IV that we analyzed a simple non-inverting, op amp circuit using the OPA627. Now we will show how this noise can be measured using a true rms meter. Fig. 6.7 illustrates the test configuration for the OPA627. Note that the measured result for this test configuration compares well to the calculated and simulated values from those Parts (ie calculated 325 µV, and measured 346 µV). Fig. 6.8 gives a step-by-step procedure for measuring noise.
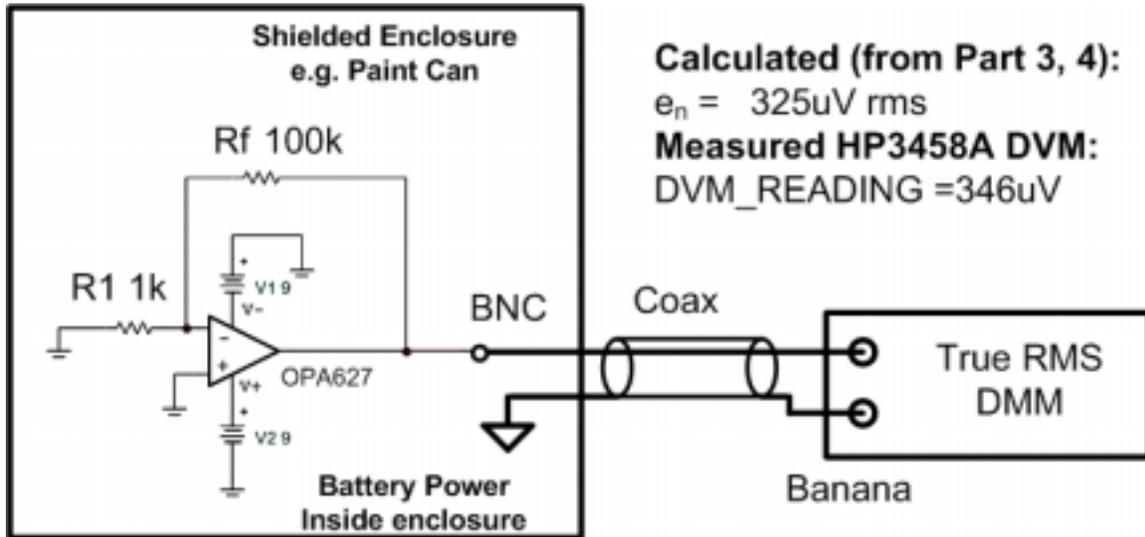

Fig. 6.7: Measuring OPA627 Circuit Noise with a True Rms Meter

1. Verify the noise floor of the measurement equipment (eg true rms DVM). This is typically done by shorting the input to the equipment
2. Check the specifications to ensure that the measurement equipment has the appropriate bandwidth and accuracy for the proposed reading. Check the equipment specifications to see if the instrument has special modes of operation that would optimize the reading
3. Place the circuit under test inside a shielded enclosure. The enclosure should be connected to signal ground. Take care to minimize the size of any holes cut in the enclosure
4. Use battery power to minimize noise, if possible. Linear power supplies are also low noise but switching power supplies are typically very noisy and will probably be the dominant source of noise if used
5. Use shielded cables to connect the circuit under test to the measurement equipment
6. Ensure that the circuit is functioning. In our example, the OPA627 has a typical offset voltage specified at 40 µV and the circuit gain is 100, so you would expect to see an output voltage of 4 mV dc. This number will very from device to device, but you would not expect to see an output of several volts
7. Measure the noise using different instruments and compare the results. Using an oscilloscope and a True rms DVM is a good approach because you can see the wave shape on the oscilloscope. The oscilloscope wave shape tells you if you have white noise, 1/f noise, 60 Hz noise pick-up, or an oscillation. The oscilloscope will also give you a rough idea of the peak-to-peak noise level. The true rms DVM, on the other hand, does not give information about the type of noise, but it does give an accurate rms noise result. A spectrum analyzer is also a great tool in noise analysis because it highlights any problems at discrete frequencies (eg noise pick-up, or noise peaking)
8. Compare the measured result to a calculated and simulated result if possible. In general it is possible to get good agreement between calculated and measured results

Fig. 6.8: Procedure for Measuring Noise

Measure the OPA627 Example Circuit Using an Oscilloscope

Fig. 6.9 shows how the circuit from Parts III and IV can be measured using an oscilloscope. In the case of the oscilloscope, look at the noise waveform and estimate the peak-to-peak value. Assuming the noise has a Gaussian distribution, you can divide by 6 to get an approximation of the rms noise (see Part I for details). The measured oscilloscope output is approximately 2.4 mVp-p, so the rms noise is 2.4 mVp-p ÷ 6 = 400 µVrms. This compares well to the calculated and simulated values (ie calculated 325 µV, and measured 400 µV).
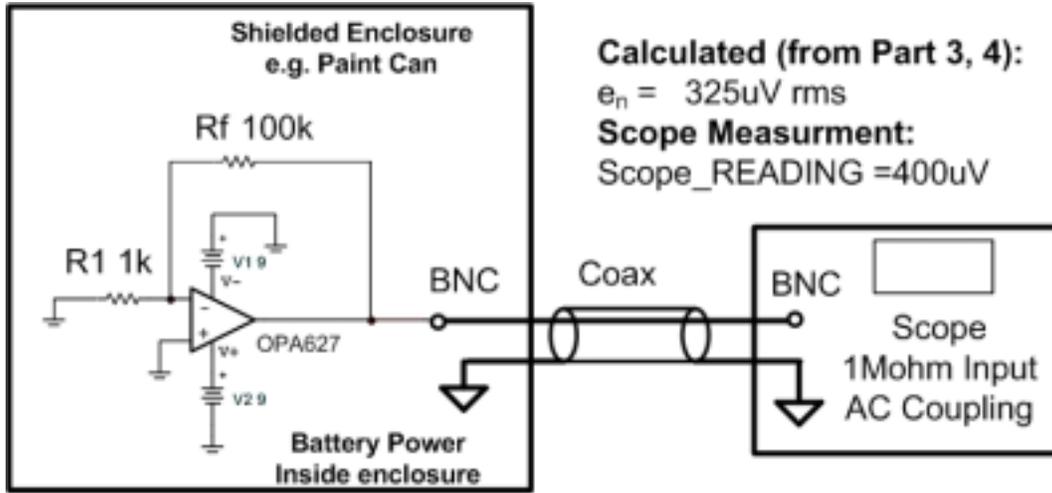
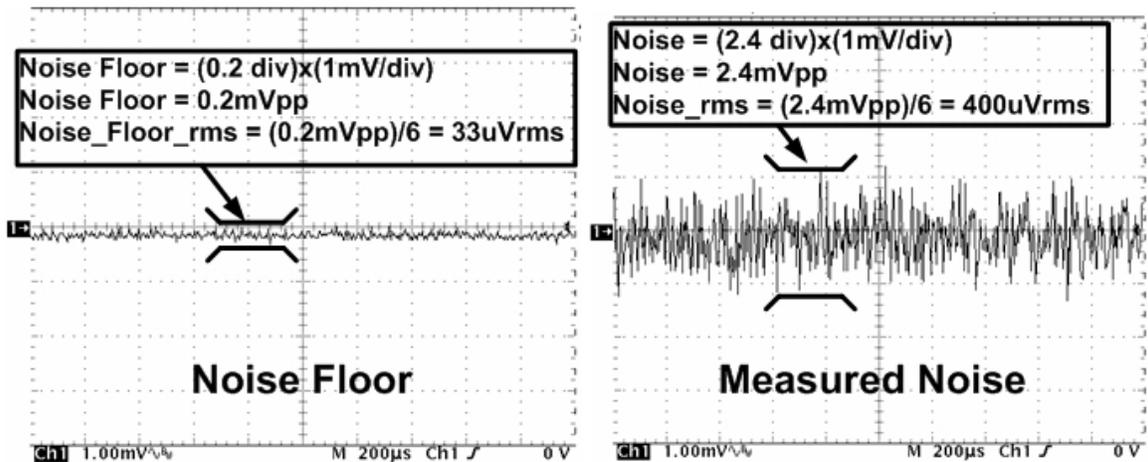**Fig. 6.9: Measuring the OPA627 Circuit Noise With an Oscilloscope**

Fig. 6.10: Results on Scope

Measure Low-Frequency Noise for the OPA227

Many data sheets have a specification for the peak-to-peak noise from 0.1 Hz to 10 Hz. This effectively gives an idea of the op amp low-frequency (ie 1/f) noise. In some cases this is given as an oscilloscope waveform. In other cases this is listed in the specification table. Fig. 6.11 shows one effective way of measuring the 0.1 Hz to 10 Hz noise. This circuit uses a second-order 0.1 Hz high-pass filter in series with a fourth-order 10 Hz low-pass filter. This circuit also provides a gain of 100. The device under test (OPA227) is placed in a high-gain configuration (noise gain = 1001) because the expected 1/f noise is very small and must be amplified to a range where standard test equipment can be used to measure it. Note that the total gain for the circuit is 100,100 (ie 100 x 1001). Thus, the output is divided by 100,100 to refer the signal to the input.
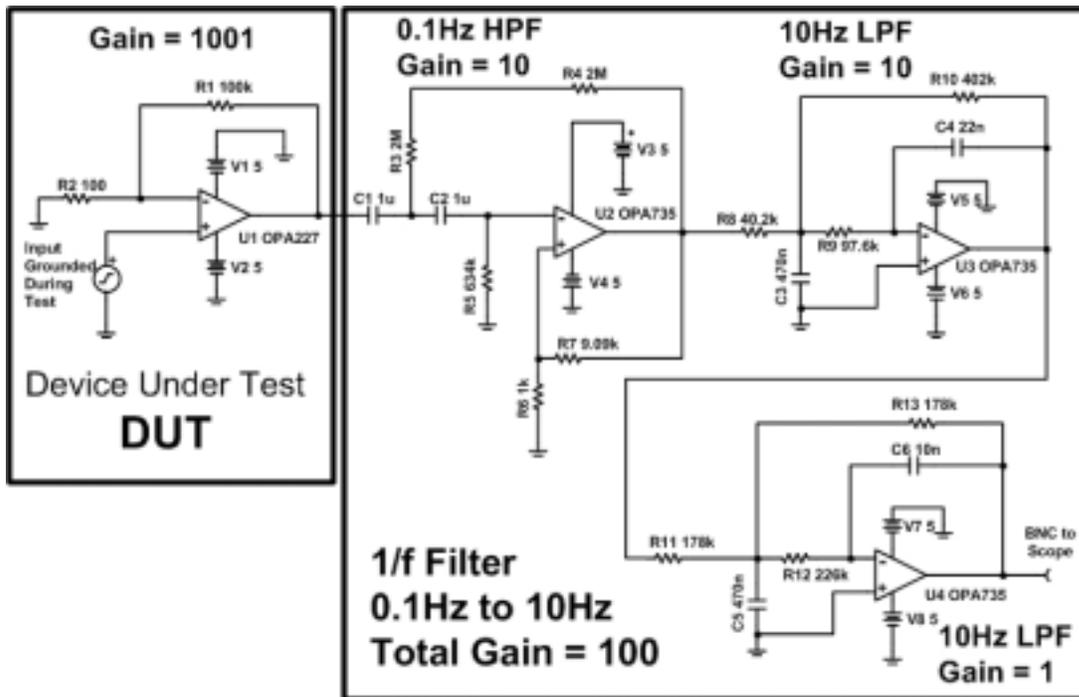

Fig. 6.11: Low-Frequency Noise Measurement Test Circuit.
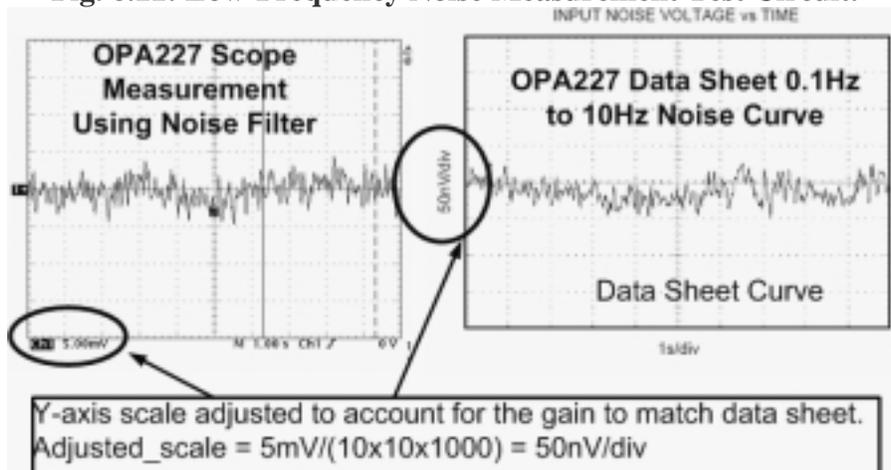

Fig. 6.12: Results for Low-Frequency Noise Measurement Test Circuit

The measured output of the circuit is shown in Fig. 6.12 and also shows a graph taken from the OPA227 product data sheet. The range of the measured result can be referred to the op amp input by dividing by the total gain (i.e., divide by 5 mV ÷ 100,100 = 50 nV). Note that the product data sheet curve compares well to the data sheet curve as expected.

Offset Temperature Drift vs 1/f Noise in Low Frequency Noise Measurement

One problem in measuring the 1/f noise of an amplifier is that it is often difficult to distinguish 1/f noise from offset drift with temperature. Note that ambient temperature fluctuates ±3°C in a typical lab environment. Air turbulence around a device can cause low-frequency variations that are in the offset that look similar to 1/f noise. Fig. 6.13 compares the output of an OPA132 in a thermally-stable environment with the same circuit in a typical lab environment. Assuming worst case op amp drift specifications, the offset drift in a typical lab environment would be about 60 µV (ie from the data sheet (10 µV/°C)(6°C) = 60 µV). The amplifier has a gain of 100, so the output drifts approximately 6 mV (ie 60 µV * 100 = 6mV).

One way to separate the effects of offset drift from 1/f noise is to place the device under test in a thermally-stable environment. This environment must keep the device at constant temperature (ie ±0.1°C) throughout the measurement. Also, temperature gradients should be reduced as much as possible. A simple way to achieve this goal is to fill the paint can with an electrically inert fluid and submerge the entire assembly during test. Heat transfer fluorinated fluids are commonly used for this type of testing because of their high electrical resistance, and high thermal resistance. Also, they are inert biologically and non-toxic. [2]
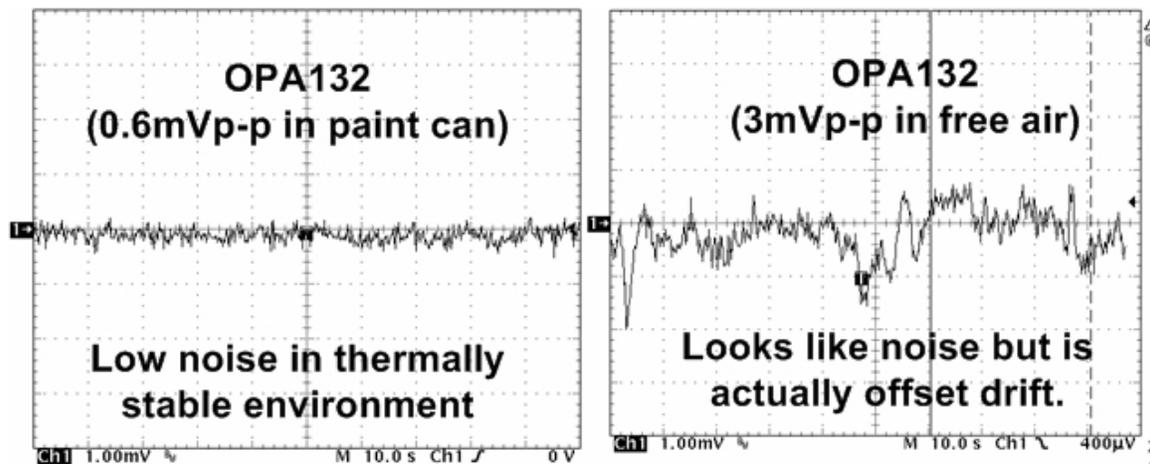

Fig. 6.13: OPA132, Lab Environment Vs. Thermally-Stable Environment

Measure the Noise Spectral Density Curve for the OPA627

As we have seen in this TechNote series, the spectral density specification is an extremely important tool in noise analysis. Although most data sheets provide this information, engineers sometimes measure their own curve to verify the published data. The circuit shown in Fig. 6.14 shows a simple test set-up that will allow voltage noise spectral density measurements.
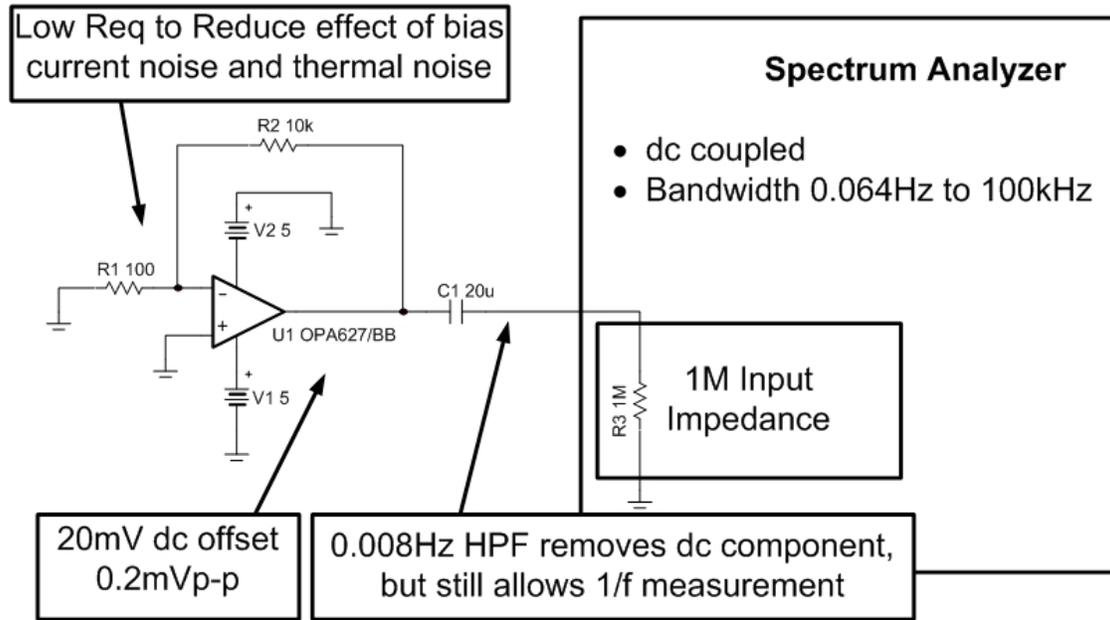

Fig. 6.14: Circuit for Measuring the Noise Spectral Density of an Op Amp

Note that the spectrum analyzer used for this measurement has a bandwidth of 0.064 Hz to 100 kHz. This bandwidth range allows characterization of the 1/f region and broadband region of many different amplifiers. Moreover, note that the spectrum analyzer is internally configured in dc coupling mode. The instrument is not configured in ac coupling mode because its lower cut frequency is 1 Hz, and this would not allow for good 1/f readings. Nevertheless, it is desirable to ac couple the op amp circuit to the spectrum analyzer because the dc offset is large in comparison to the noise. Thus, the op amp circuit is ac-coupled using the external coupling capacitor C1 is used in conjunction with the input impedance of the spectrum analyzer R3. The lower cut frequency of this circuit is 0.008 Hz (this will not interfere with our 1/f measurements because the spectrum analyzers minimum frequency is 0.064 Hz). Note that C1 is actually multiple ceramic capacitors in parallel (electrolytic and tantalum capacitors are not recommended for this application).

Another consideration with the amplifier configuration is the value of feedback network. Remember, from Part III, that the parallel combination of R1 and R2 (Req = R1‖R2) is used to compute the thermal noise and the bias current noise. The value of this resistance should be minimized so that the measured noise is only from the op amp voltage noise (ie the effect of bias current noise and resistor thermal noise is negligible).

As with all noise measurements, verify that the noise floor of the spectrum analyzer is lower than the op amp circuit. For the example shown in Fig. 6.14, the amplifier is configured in a gain of 100 to increase the output noise above the noise floor of the spectrum analyzer. Keep in mind that this configuration will limit the high frequency bandwidth (ie Bandwidth = GainBandwidthProduct ÷ Gain = 16 MHz ÷ 100 = 160 kHz). Thus, the noise spectral density curve will roll off at a lower frequency. The example is not affected by this issue because the high-frequency roll-off occurs outside the spectrum analyzer bandwidth (ie the noise rolls-off at 160 kHz and the spectrum analyzer's maximum bandwidth is 100 kHz).

Fig. 6.15 shows the result of the spectrum analyzer measurement. Note that the data was collected over several different frequency ranges (ie 0.064 Hz to 10 Hz, 10 Hz to 1 kHz, and 1 kHz to 100 kHz). This is because the spectrum analyzer in this example uses a linear frequency sweep to collect data. For example, if a data point is taken every 0.1 Hz, then the resolution is poor at low frequencies and excessive at high frequencies. Also using a small resolution over a wide frequency range would require an excessive number of data points (eg 0.1 Hz resolution and 100 kHz bandwidth would require 1×10^6 points). On the other hand, if you change the resolution for different frequency runs, you can get good resolution in each range without using an excessive number of data points. For example, the resolution from 0.064 Hz to 10 Hz could be set to 0.01 Hz, while the resolution from 1 kHz to 100 kHz could be set to 100 Hz.
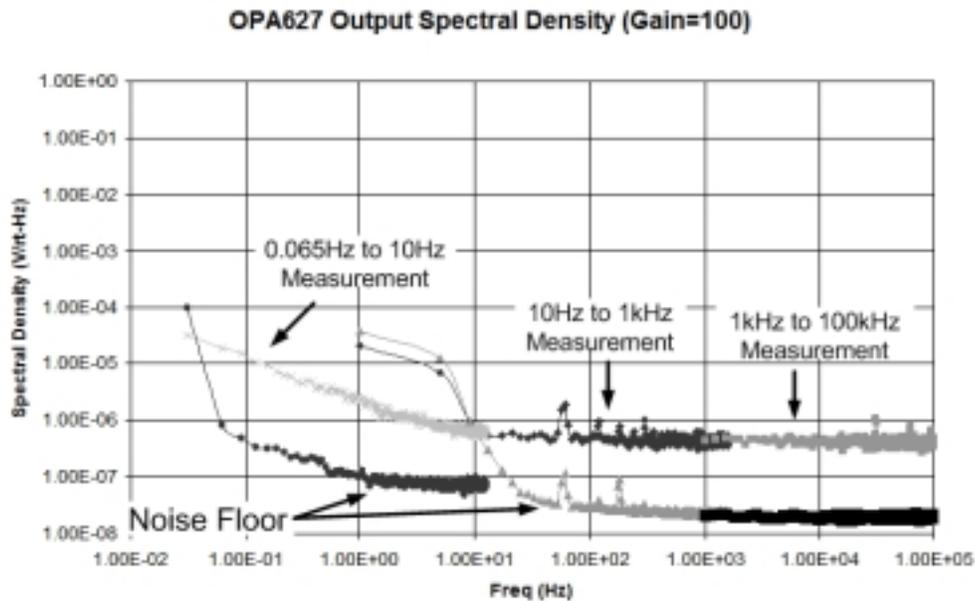

Fig. 6.15: Measure Spectral Density Over Several Ranges

Fig. 6.16 highlights some common anomalies in the spectrum analyzer results. The first anomaly is noise pickup from an external source. Specifically, this example shows noise pick-up at 60 Hz, and 120 Hz. It is also common to see pick-up from the local oscillator in the spectrum analyzer. Under ideal circumstances the noise pickup would be minimized by shielding; however, in practice this pick-up is often unavoidable. The key is to identify if the noise *spike* in the spectrum is the result of noise pick-up, or are they part of the intrinsic noise spectral density of the device.
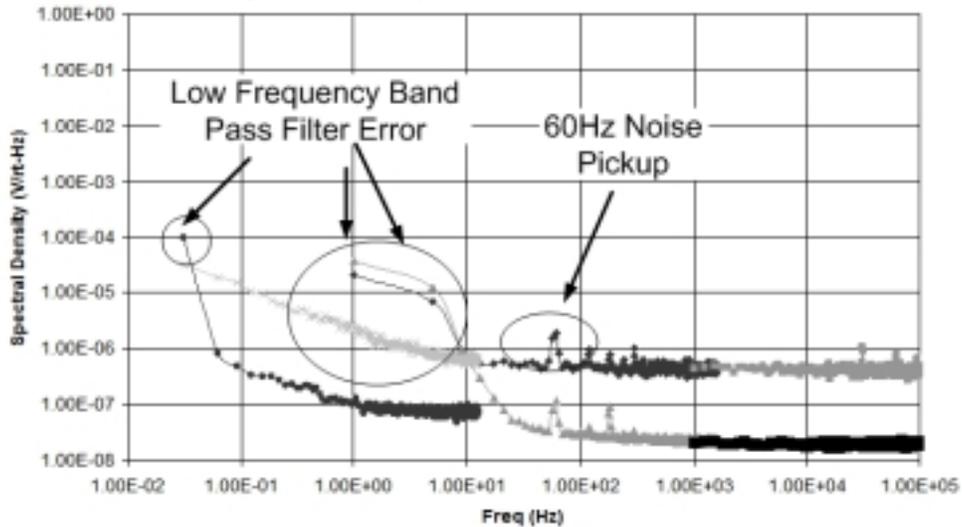
Fig. 6.16: Common Anomalies in Spectral Density Results

Another common anomaly seen in the spectral density plot (Fig. 6.15) is the relatively large error that occurs at the minimum frequency for a given measurement range. To better understand this error, consider that the spectrum is measured by sweeping a bandpass filter across the entire spectrum. Assume the range is 1 Hz to 1 kHz and the resolution bandwidth of the bandpass filter is 1 Hz. For this frequency range the bandpass filter is relatively narrow at the high frequencies, and relatively wide at the low frequencies. Now consider that at the low frequencies the skirts of the band pass filter will pick up large errors from 1/f noise. Fig. 6.17 graphically illustrates this error.
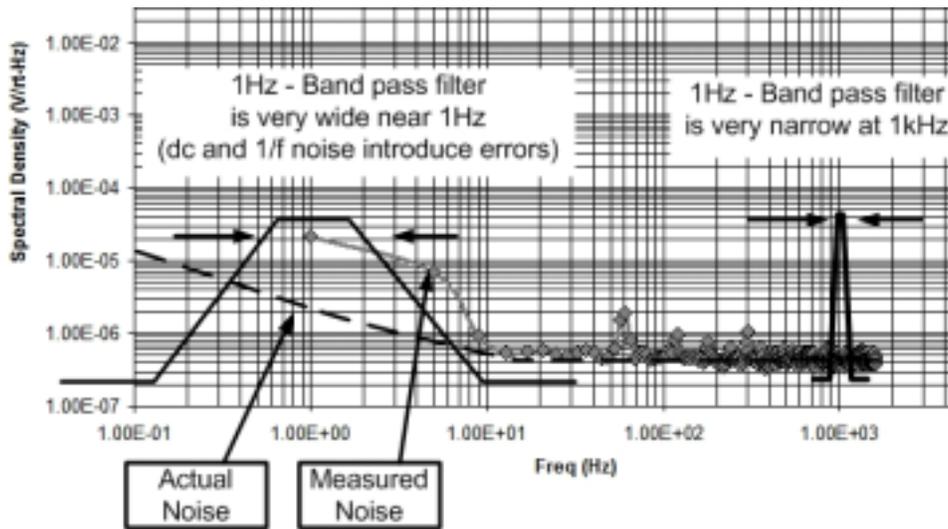
Fig. 6.17: Measurements at Minimum Frequency Include Errors

Understanding the various measurement anomalies can be used to correct the errors. For example, by measuring the data over several ranges and discarding a few points on the low end of the frequency range you can get more accurate results. In our example, the, range from 0.0625 Hz to 10 Hz overlaps the range from 10 Hz to 1 kHz. The (10 Hz, 1 kHz) range contains some erroneous data below 10 Hz. This erroneous data is discarded. Noise pickup (eg 60 Hz pickup) can be omitted from spectral density measurements because it is not part of the intrinsic op amps noise.

Fig. 6.18 shows the noise spectral density curve from our example measurement with the anomalous readings eliminated. The data were also divided by the test circuit gain so that the spectral density is referred to the input of the op amp. Finally, the data was averaged.
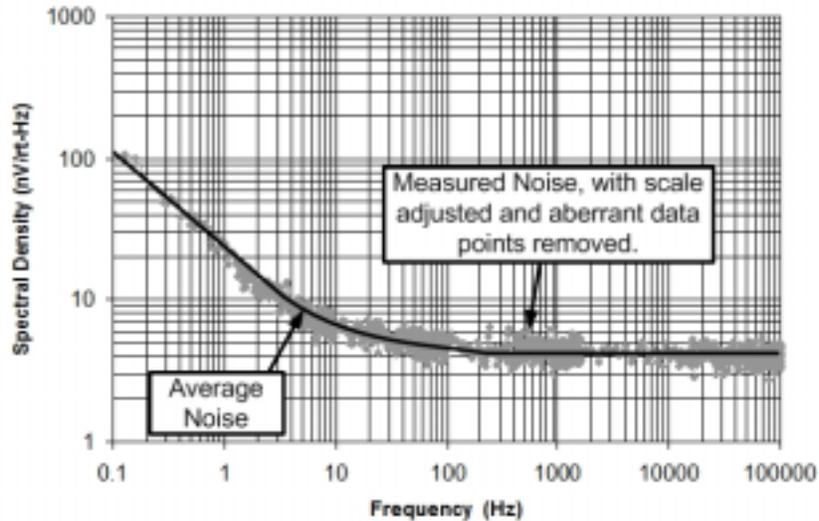

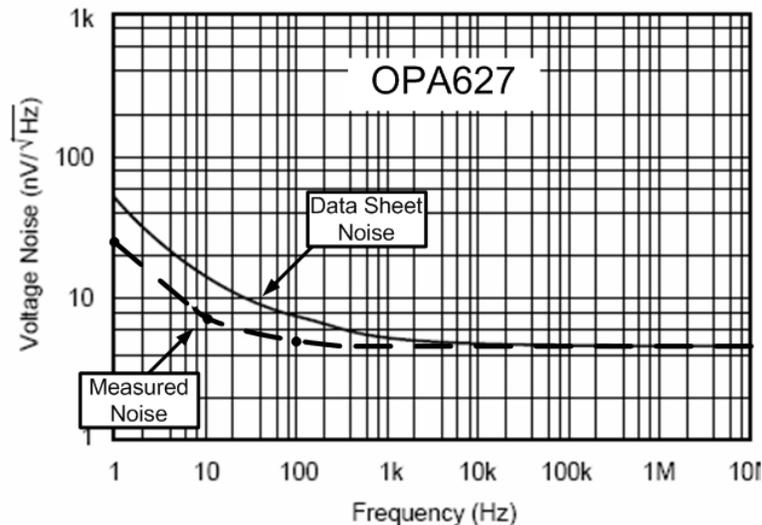Fig. 6.18: Spectral Density: Measured Results

Fig. 6.19: Comparing Measured Spectral Density to Data Sheet

Comparing the spectral density measurement for the OPA627 to the data sheet curve (Fig. 6.19) is interesting. For broadband noise the match is close, but the 1/f noise measurement is not. Actually, the deviation of the 1/f noise from the specification is not a very unusual result. In Part VII of this series, we will discuss this topic in detail.

Summary and Preview

In this TechNote we have covered several different noise measurement examples. The methods illustrated in the examples can be used for most general analog circuits. In Part VII we will discuss topics related to the internal design of the op amp. Understanding the fundamental relationships that define the noise inside an op amp will help board-and-system level designers have insight into noise characteristics that are not specified in most data sheets. Specifically, worst case noise, noise drift, and the difference between CMOS and Bipolar will be discussed.

References

[1] Henry W Ott, *Noise Reduction Techniques in Electronic Systems*, Second Edition, Published by John Wiley & Sons, Inc
[2] http://www.solvaysolexis.com/

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Arthur Kay is a senior applications engineer at Texas Instruments where he specializes in the support of sensor signal conditioning devices. Prior to TI, he was a semiconductor test engineer for Burr-Brown and Northrop Grumman Corp. He graduated from Georgia Institute of Technology with an MSEE in 1993. Art can be reached at ti_artkay@list.ti.com