Making Accurate Voltage Noise and Current Noise Measurements on Operational Amplifiers Down to 0.1Hz

AN1560
Rev.1.00
Jan 11, 2011

Abstract

Making accurate voltage and current noise measurements on op amps in the nV and fA range can be challenging. This problem is often addressed by two different approaches. Both approaches concentrate on reducing the noise of the amplifiers used to measure the Device Under Test (DUT). The first approach uses conventional cross-correlation techniques to remove un-correlated noise and a procedure to remove the correlated noise contributions made by the amplifiers used to measure the DUT [1]. The second approach, and the subject of this Application Note, consists of designing a test platform with an effective background noise at least 10dB lower than the DUT.

To obtain a test platform with this level of performance requires: the removal of environmental electrical disturbances, the use of batteries for low noise voltage sources, the use of a Post Amplifier (PA) to raise the DUT noise above the measurement system's noise floor, control software to measure accurate noise data down to 0.1Hz and processing software to eliminate external noise and generate the DUT's voltage (e_n) and current (i_n) noise plots.

This Application Note will discuss the procedures used to obtain a test platform that is capable of measuring nV and fA down to 0.1Hz. The test platform's capability is illustrated by measuring the voltage and current noise of Intersil's ISL28190 (Bipolar inputs, 1nV/√Hz) operational amplifier and Intersil's ISL28148 (MOS inputs, 16fA/√Hz) operational amplifier.

Introduction

To measure an accurate internal noise of an Op Amp, for a data sheet spec, two types of external noise sources (Environmental and Johnson) must be removed from the measurement. Environmental noise is any unwanted signals arriving as either voltage or current, at any of the amplifiers terminals or surrounding circuitry. It can appear as spikes, steps, sign waves or random noise. This noise can come from anywhere: nearby machinery, power lines, RF transmitters, lab power supplies or lab computers. The Environmental noise is minimized by isolating the DUT in a Faraday cage and powering the DUT with batteries.

The second external noise source is Johnson noise. Johnson noise is the noise generated by the external biasing and gain setting resistors of the DUT and test platform. Johnson noise is subtracted out from the total noise measurement through processing software so only the internal noise of the DUT is reported.

This Application Note will:

1. Discuss basic noise equations (external and internal) and then use these equations to extract the DUT noise from our test platform's noise.
2. Discuss the use of a Post Amplifier (PA) to lower our HP35670A Dynamic Signal Analyzer's (DSA) effective noise floor from 20nV/√Hz to 3nV/√Hz.
3. Illustrate the effectiveness of our Faraday cage to remove environmental noise.
4. Discuss AC coupling of DUT, PA and DSA.
5. Determine the required gain of the DUT to enable the test platform to measure voltage noise below 3nV/√Hz.
6. Discuss considerations for choosing the optimum series resistor R_S to measure current noise.
7. Discuss the Test Platform Algorithm.
8. Present conclusions.

Basic Equations For Calculating Noise

Johnson noise is the only resistive noise source considered in this controlled lab study. Other resistive noise sources such as contact noise, shot noise and parasitics associated with particular types of resistors could also contribute noise in an application.

A typical figure of merit for amplifier noise is noise density. Voltage-noise density is specified in nV/√Hz, while current-noise density is usually in units of pA/√Hz [2]. For simplicity, these measurements are referred to the amplifier inputs; thus removing the need to account for the amplifiers gain.

External Johnson Noise

At temperatures above absolute zero, all resistances generate Johnson noise due to the thermal movement of charge carriers. This noise increases with resistance, temperature and bandwidth. The voltage and current noise are given by Equations 1 and 2, respectively [3, 4, 5].

External Johnson Voltage Noise

$$V_n = e_n = \sqrt{4kTBR} \qquad \text{(EQ. 1)}$$

External Johnson Current Noise

$$i_n = \sqrt{\frac{4kTB}{R}} \qquad \text{(EQ. 2)}$$

Where:

k is Boltzmann's constant (1.38×10^{-23} J/K).

T is the temperature in Kelvin (273.15 + Ambient °C).

R is the resistance (Ω)

B is the bandwidth in Hz.

Note: Bandwidth is 1Hz for all measurements and not shown in all Equations presented in the Application Note.

Internal Noise of the DUT

Figure 1 shows the internal noise of an Op Amp referenced to the amplifiers inputs. Measurements Referenced To the Input are referred to as RTI. To generate this curve, the external noise has been removed from the final values shown along with any gain the measurement circuits may have added. The internal noise of an amplifier has two distinct frequency ranges. At very low frequencies, the noise amplitude is inversely proportional to frequency and is referred to as the 1/f noise. At frequencies above the corner frequency, the noise amplitude is essentially flat.

Equation 3 is used to calculate the total noise voltage Referenced To the Output (RTO) for the basic Op Amp in Figure 2.

$$e_t = \sqrt{e_n{}^2 + (R_S \times i_n)^2 + (R_1 \| R_2 \times i_n)^2 + 4kT(R_S + R_1 \| R_2)} \times A_V \quad \text{(EQ. 3)}$$

Where:

e_t = Total voltage noise RTO at a given frequency.

e_n = RTI voltage-noise of DUT at a given frequency.

$R_1 \,||\, R_2 = R_1R_2/(R_1 + R_2)]\Omega$

i_n = RTI current-noise of the DUT at a given frequency.

k = Boltzmann's constant (1.38 x 10^{-23} J/K).

T = Ambient temp in Kelvin (273.15 + Ambient °C).

A_V = Gain of Op Amp (1 + R_1/R_2).

Procedure to Improve the DSA's Effective Noise Floor

Figure 3 shows the noise floor of the HP35670A DSA measured with the input grounded. From this graph, the minimum noise floor is around 20nV/√Hz. A technique to improve the measurement noise floor of the test platform is to add a Post Amplifier to gain the noise being measured above the noise floor of the DSA. Figure 4 shows the final test platform schematic which includes the DSA, HA-5147 PA, DUT and the AC coupling of the DUT offset and the PA offset voltage. Note: the HA-5147 was cherry picked for its low (11nV/√Hz at 0.1Hz) 1/f noise performance.

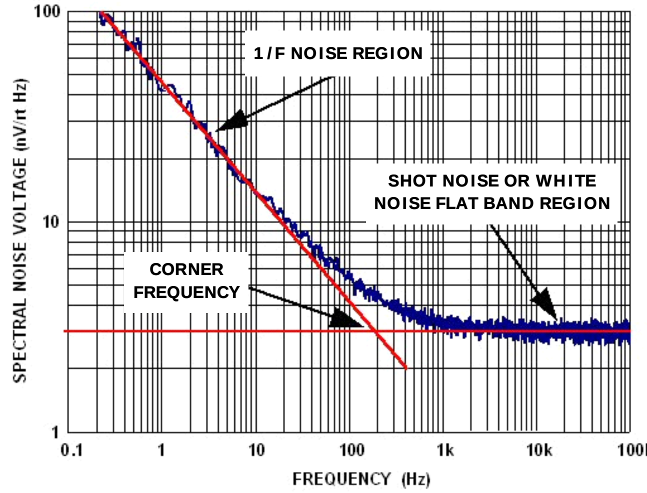

FIGURE 1. AMPLIFIER INTERNAL VOLTAGE NOISE (RTI) vs FREQUENCY

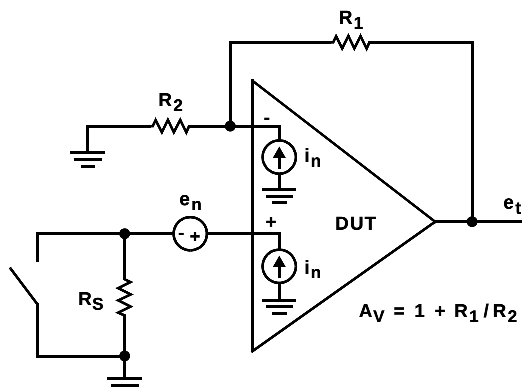

FIGURE 2. OP AMP NOISE MODEL

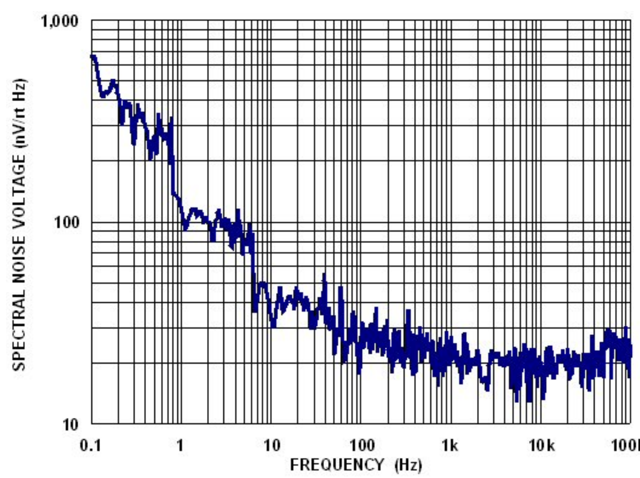

FIGURE 3. NOISE FLOOR OF THE HP35670A DYNAMIC SIGNAL ANALYZER

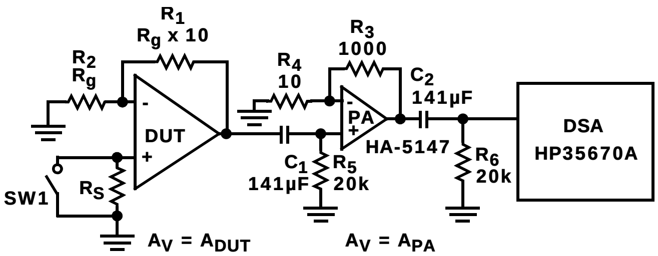

FIGURE 4. COMPLETE LOW NOISE TEST PLATFORM SCHEMATIC

The minimum gain of the PA is the gain that overcomes the noise floor of the DSA down to 0.1Hz frequency. Figure 5 shows the noise floor of the HP35670A DSA (pink curve), the RTO noise voltage of the PA with the gain set to 26 (blue curve), and the RTO noise voltage of the PA with the gain set to 101 (green curve). Notice that the gain of 26 is not enough and the PA's RTO noise voltage is swamped out by the DSA's noise floor for frequencies less than 10Hz. Setting the PA's gain to 101 is enough to overcome the DSA noise floor by 20dB at 1kHz and 3.3 dB at 0.1Hz.

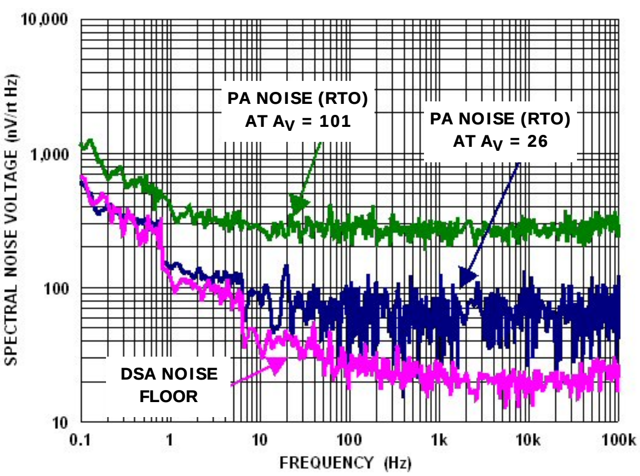

FIGURE 5. SETTING THE GAIN OF THE POST AMPLIFIER TO OVERCOME THE RTO DSA NOISE FLOOR

Figure 6 shows the RTI noise voltage of our PA set to a gain of 101 (green trace) and the original DSA noise floor (pink trace) repeated for comparison purposes. By referencing the PA noise to the input, (dividing by A_V = 101) we are now able to effectively measure a flat band RTI noise of 3nV/√Hz, which is the noise floor of our HA-5147.

Faraday Cage to Remove Environmental Noise

Figure 7 shows the result of testing an HA-5147 (A_V = 101) inside and outside our Faraday cage. The Faraday cage enables us to maintain a noise floor of 3nV/√Hz over an additional decade of frequency in the flat band region. For frequencies below 100Hz, the improvement in the noise floor is critical in making noise measurements down to 0.1Hz. For frequencies above 100Hz, environmental noise was not a factor for our given lab conditions.

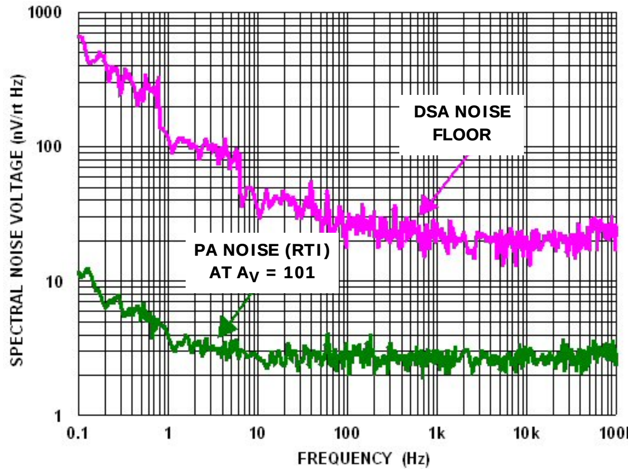

FIGURE 6. EFFECTIVE RTI 3nV/√Hz NOISE FLOOR OF THE PA AND DSA

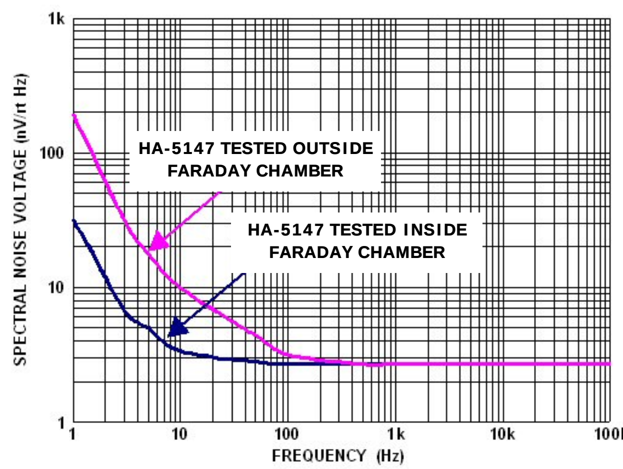

FIGURE 7. EFFECTS OF FARADAY CAGE ON LOW FREQUENCY ENVIRONMENTAL NOISE

AC Coupling of the Post Amp and the DUT

The output of the PA and DUT need to be AC coupled to avoid over-driving the DSA's input or railing the output of the PA, as a result of the DC offset caused by VOS and Ib (reference Figure 4). The subsequent measurements were performed on the PA and DSA to minimize any errors before measuring any noise on the DUT.

Initially, the test platform used the internal AC coupling of the HP35670A DSA. Test results at frequencies below 10Hz were artificially low, when compared to the expected results for HA-5147 at 1Hz. The cause of the error was determined to be the internal AC coupling circuitry of our DSA. Figure 8 shows the effective roll-off in gain of the DSA's internal AC coupling circuit (red trace) compared to the roll-off in gain when using an external AC coupling