Decrease testing time for quality control of op amp noise

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Introduction

Industrial and high-precision applications require strict control over non-deterministic noise. Some testing may be required to assure system quality because the typical noise value denotes the mean value of a parameter in a population of devices, and does not guarantee that individual devices will not exceed a certain level.

Devices without guaranteed noise parameters may be rapidly tested to ensure quality. Most product data sheets for operational amplifiers (op amps) specify a typical value for 1/f noise (also known as flicker noise) for a range from 0.1 Hz to 10 Hz. Conventionally, testing devices in these situations require tens or hundreds of seconds per device, vastly increasing time-to-market and production costs.

Additionally, measuring noise density across a wide bandwidth may not be relevant in all systems or applications. To address the issue, this article uses existing theory and empirical data to explore test methodology for quickly testing for noise on any portion of the 1/f region. Furthermore, theoretical and real-world results are compared using the OPA1652 low-noise audio op amp from Texas Instruments.

Description and theory

The voltage noise-density curve of the classic op amp (Figure 1) has two regions: a frequency-independent region known as the broadband noise region; and a frequency-dependant region known as the 1/f noise region. The 1/f noise region refers to 1/f noise which, as the name suggests, exhibits a 1/f slope with respect to frequency. The 1/f noise is dominant at lower frequencies and decreases at higher frequencies. This means that it takes longer to measure than broadband noise. Low-frequency signals take longer to measure since their cycles take longer to complete in the time domain. The point at which broadband noise is equal to 1/f noise is called the corner frequency. The corner frequency for bipolar and CMOS amplifiers varies by architecture and process. Generally, bipolar amplifiers have a lower corner frequency than CMOS amplifiers.

This article presents noise as a density function, with voltage noise density having the units of $V/\sqrt{Hz}$. The voltage noise exhibited can be calculated by integrating the power spectral density between two frequencies of interest (f_1 and f_2), rather like a probability density function. The integrated voltage noise is calculated using e_n as noise spectral density:

$$V_{RMS} = \sqrt{\int_{f_1}^{f_2} (e_n)^2 df} \quad (1)$$

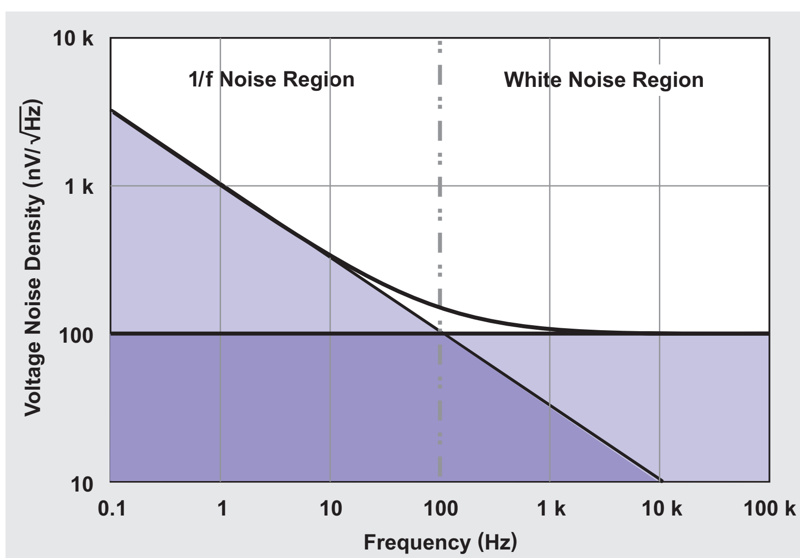
The combination of broadband noise and 1/f noise of an op amp (Equation 2) is obtained by taking the square root of the sum of the squares of RMS values of the broadband component and 1/f component, respectively. This is possible because broadband noise and 1/f noise are modeled as uncorrelated noise sources.

Total RMS voltage noise:

$$E_{n\_T} = \sqrt{E_{nf}^2 + E_{nBB}^2}, \quad (2)$$

where E_{nf} = 1/f RMS noise [V_{RMS}] and E_{nBB} = broadband RMS noise [V_{RMS}].

Figure 1. Voltage noise-density curve



In the datasheet, the noise in the 1/f region is generally expressed in terms of peak-to-peak noise over a range of frequency, while broadband noise is expressed as a voltage noise density at a particular frequency. The units for noise spectral density are $V/\sqrt{Hz}$. The individual noise components can be calculated by using the following equations, assuming a fixed noise spectral density.

Integrated broadband noise (broadband noise constant over frequency):

$$E_{nBB} = e_{BB} \times \sqrt{BW_n}\ , \tag{3}$$

where e_{BB} = broadband spectral noise density [$V/\sqrt{Hz}$] and BWn = bandwidth [Hz].

The integrated 1/f noise component:

$$E_{nf} = e_{fnorm} \times \sqrt{\ln(f_H / f_L)}\ , \tag{4}$$

where e_{fnorm} = normalized noise density at 1 Hz from Equation 5 [$V/\sqrt{Hz}$], f_H = upper frequency band limit [Hz], and f_L = lower frequency band limit (0.1 Hz typically) [Hz].

Normalized noise density at 1 Hz in 1/f region:

$$e_{fnorm} = e_{known} \times \frac{\sqrt{f_{known}}}{\sqrt{1 Hz}}\ , \tag{5}$$

where e_{known} = known voltage noise density in 1/f region [$V/\sqrt{Hz}$] and f_{known} = frequency in 1/f region where noise density is known [Hz].

The detailed calculations are shown in Reference 1 and are beyond the scope of this article.

The Problem

In noise-sensitive applications, choosing an op amp with minimal noise is critical for maintaining accuracy and precision. When selecting the op amps suitable for the application, screening may be required to remove any outliers. Testing for broadband noise occurs rapidly, since kHz cycles can be measured in just a few milliseconds. However, the same cannot be said for the 1/f noise component. Measuring the 1/f noise region can require anywhere from 0.1 seconds upwards to several minutes, depending on the bandwidth and level of averaging. This is because a cycle of the 0.1-Hz signal takes at least 10 seconds to complete. When averaging, the required time becomes even longer. Additionally, when performing a fast Fourier transform (FFT) to calculate noise density, the resolution bandwidth required may entail many hours of test time. This calls for a quick and precise way to extrapolate the 1/f noise of the op amp.

A quick and simple solution

The quickest way to test the 1/f component of the amplifier is to use Equations 4 and 5 to extrapolate. The 1/f integrated noise is proportional to the square root of the natural logarithm of the ratio of two frequencies (f_L, f_H), over which the 1/f noise is to be determined. Extending this further, one can say that a 1/f RMS noise component depends on the ratio of two frequencies: f_H and f_L. An example calculation is given by calculating 1/f RMS noise with voltage noise-density curve given (Figure 1).

To calculate 1/f RMS noise over the two ranges, 1 Hz to 10 Hz and 10 Hz to 100 Hz, assume an ideal 1/f curve with known normalized noise density e_{fnorm} at 1 Hz. Both ranges are located in the 1/f dominated portion on the noise spectral-density curve (Figure 1). This ensures a negligible error contribution from the broadband noise portion. Equation 4 is used to compare noise for the two ranges:

$$E_{nf} = e_{fnorm} \times \sqrt{\ln(f_N / f_L)}$$

$$E_{nf1} = e_{fnorm} \times \sqrt{\ln(10/1)} \text{ and } E_{nf2} = e_{fnorm} \times \sqrt{\ln(100/10)}$$

$$E_{nf1} = e_{fnorm} \times \sqrt{\ln 10} \text{ and } E_{nf2} = e_{fnorm} \times \sqrt{\ln 10}$$

$$E_{nf1} = e_{fnorm} \times \sqrt{\ln 10} = E_{nf2} = e_{fnorm} \times \sqrt{\ln 10}$$

Notice how the equations for E_{nf1} and E_{nf2} render the same value for 1/f RMS noise. This is because this equation is dependent on the ratio of the two frequency limits, not the frequencies themselves. There are three critical conditions for this rule of thumb to apply:

1. The 1/f curve must approximate 1/f on the power spectrum or $1/\sqrt{f}$ on the noise spectrum,
2. The area of interest must be in a 1/f-dominated region of the noise spectrum, and
3. The ratios must be the same.

Using this method, one can estimate 1/f RMS noise of an op amp from 0.1 Hz to 10 Hz by screening the op amp from 10 Hz to 1 kHz, as long as the frequencies aforementioned are in the 1/f dominated region. This change in frequency of interest improves a device's test time by a factor of 100 or more. Instead of waiting for 10 seconds for a sample to be acquired; a sample could be taken in 100 milliseconds. The most time savings are with CMOS amplifiers because the corner frequency is greater than it is for bipolar amplifiers. The graphs in Figures 2 and 3 show that the peak-to-peak noise level of an amplifier is the same over different frequency ranges, assuming the ratio of the frequencies is equal and the measurements are in the 1/f dominant region.

Conclusion

The technique of extrapolating the 1/f noise component only holds if all frequencies are lying in the 1/f-dominated region. This technique performs with high accuracy as long as the chosen bandwidth for extrapolation is sufficiently far away from the corner frequency, because the broadband noise component is significant in this region. Additionally, the 1/f curve must approximate 1/f on the power spectrum or $1/\sqrt{f}$ on the noise spectrum. Most classical semiconductor op amps follow this rule, notable exceptions being chopper or auto-zero amplifiers that do not have a 1/f noise region. One example is the low-noise, zero-drift OPA2188.

Acknowledgments

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Figure 2. Voltage noise from 0.1 Hz to 10 Hz

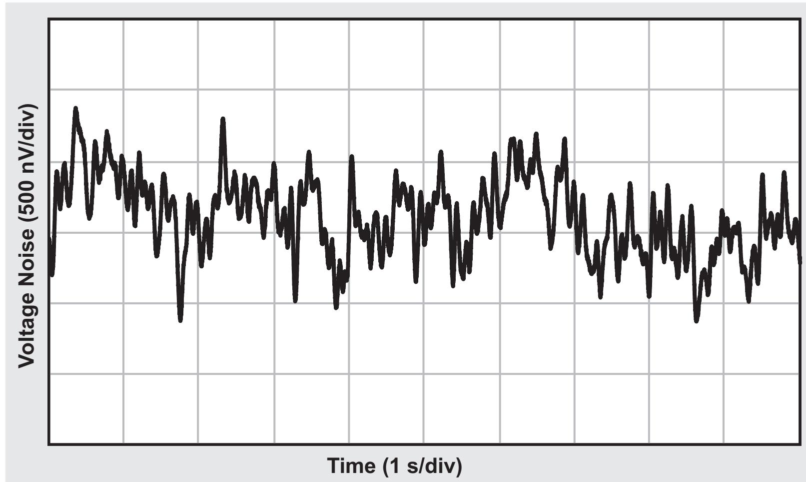
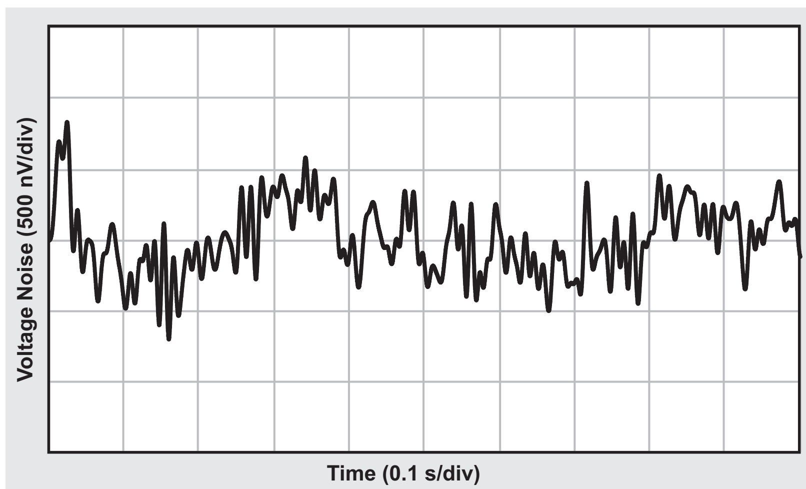


Figure 3. Voltage noise from 1 Hz to 100 Hz



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