SPECIFYING AND MEASURING
A LOW NOISE FET-INPUT IC OP AMP, THE AD514

by Bill Maxwell

The AD514* is a FET-input integrated-circuit operational amplifier designed to provide at low cost the benefits of moderately low drift and bias current, and a guaranteed peak-to-peak noise level at low frequencies, in the "1/f" region. The amplifier is designed for applications that call for high input impedance and low noise, where low cost is essential. Applications for which it is well-suited include ecg and eeg amplifiers, pH-electrode amplifiers, and long-term integrators. For such applications, low noise, with predictable characteristics, in the 0.1 to 10Hz band, is well-nigh essential. For the AD514L, maximum voltage noise of 5μV p-p is guaranteed by testing all units.

Since IC op amps with guaranteed low-frequency noise specifications have not until now been available in quantities and at prices that are conducive to high-volume usage, the decision to break new ground by making such an amplifier available has posed certain problems in the area of characterization, interpretation of specifications, and the design of on-line test equipment.

A BRIEF REVIEW OF NOISE

Since the statistical nature of noise is at the heart of these problems, it may be useful to review a few basic noise relationships[1], particularly as they pertain to op-amp performance. We are concerned here with the irreducible noise generated within the amplifier itself, excluding all external interference sources, such as the power supplies, associated components, and fields in the vicinity of the device, which might cause noise to be induced, coupled, or conducted into the circuit.

Like drift (itself partly a low-frequency noise phenomenon), noise originating within the amplifier may be referred to the input circuit. The three fairly-uncorrelated effects (in FET-input op amps at low frequency) are a noise voltage in series with either input and noise currents from both inputs to common. Voltage noise is amplified by the closed-loop gain (i.e., "noise gain") of the feedback-amplifier circuit; current noise develops voltage across impedances connected to the input terminals, and it may or may not be amplified, depending on the circuit configuration. In single-ended amplifier circuits, especially inverters, only one of the two current sources is usually of interest, since the other input is connected to a low impedance.

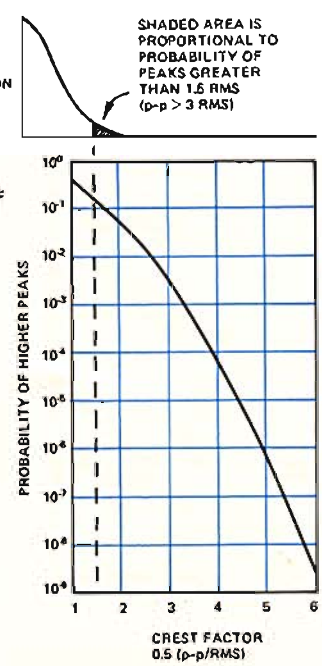
Though noise is random, and its value at any instant of time is unpredictable, most types of noise found in semiconductor circuits do have stationary properties, hence consistently-measurable amplitude distributions and frequency spectra. This means that noise in a given bandwidth can be characterized by its root mean-square (rms) value. Since noise from independent sources, and noises in different bands of the spectrum (from the same source) are all uncorrelated, they may be combined by root sum-of-the-squares summation. For example, if the rms voltage noise in the band 10Hz to 100Hz amounts to 0.13μV, and the noise in the band 100Hz to 1kHz is 0.2μV; and if the noise generated in a signal source resistance is 0.41μV over the band 10Hz to 1kHz, the total rms input noise to the amplifier due to these sources will be

$$E_n = \sqrt{0.13^2 + 0.2^2 + 0.41^2} = 0.47\mu V \qquad (1)$$

Note that the squaring causes the summation to be dominated by the largest term. Usually, we can neglect noise components less than 1/3 of the largest component (in this case, if we were to neglect the 0.13μV term, the sum would be 0.46μV).

RMS vs. "PEAK-TO-PEAK"

For many applications, especially in "one-shot" measurements at low frequency, rms noise is not very meaningful, because it represents the result of an averaging process. Rather, we might be concerned about the effects of instantaneous noise that occurs during the measurement. All values of noise are possible, but it can be shown that, for a "Gaussian" distribution (and many of the types we are concerned with can be assumed to have Gaussian amplitude distributions), the proportion of time occupied by peaks higher than a specified value decreases quite rapidly as a function of increasing peak amplitude. This can be shown graphically or in tabular form (Figure 1). For many practical purposes, the assumption that the largest peak-to-peak noise swing is 6.6x rms (0.1% probability) is quite tenable, and useful measurements can be made assuming even smaller ratios of peak-to-peak to rms.



P-P / RMS	PROBABILITY OF HIGHER PEAKS
2	0.32
4	0.046
6	0.0037
6.6	0.001
7.8	0.0001
8	0.000063
8.8	0.00001
9.8	0.000001
12	0.000000002

Figure 1. Crest factor of gaussian noise

*For technical data on the AD514, use the reply card. Request M2.

[1] See also: *Analog Dialogue* 3-1, "Noise and Operational Amplifier Circuits." A useful book: *Low-Noise Electronic Design*, C. D. Motchenbacher and F. C. Fitchen, John Wiley & Sons, 1973; it contains a list of further references.

THE NOISE SPECTRUM

A plot of noise vs. frequency provides useful information (Figure 2), since it may be multiplied by circuit amplitude-response spectrum to obtain the output distribution of noise vs. frequency, and hence the resulting rms noise, in any band. The function that is plotted is called the *spectral density*, and it is plotted either in "power" form ($e_n{}^2$, $i_n{}^2$), or in root-power form (e_n, i_n). If we consider the frequency range to be divided into a large number of infinitesimal frequency elements, df, then the rms noise over a given frequency band is equal to the square-root of the sum of the squares of the rms noise in each incremental band. The power spectral density is the limit of the ratio of each incremental mean-square noise contribution to the incremental band in which it occurs, in the vicinity of a frequency f. When expressed in "power" form, its dimensions are V^2/Hz or A^2/Hz; in root form, they are $V/\sqrt{Hz}$ or $A/\sqrt{Hz}$.* To obtain mean-square noise over any bandwidth, we integrate this function over the frequency range of interest, that is

$$E_n{}^2 = \int_{f_L}^{f_H} e_n{}^2 df, \text{ or for rms, } E_n = \sqrt{\int_{f_L}^{f_H} e_n{}^2 df} \qquad (2)$$

The value of e_n or i_n at a given value of frequency is called the "spot noise."

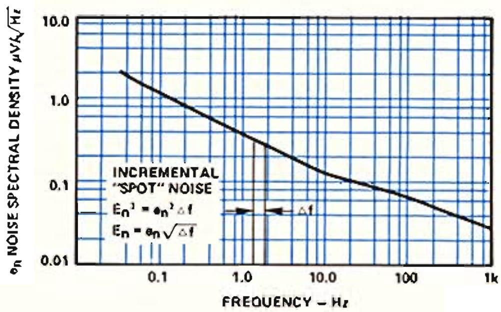


Figure 2. Voltage noise spectral density of typical AD514 operational amplifier

Despite its usefulness, the noise spectrum is difficult to acquire, even in the laboratory, especially at low frequencies, since a series of "spot" measurements generally involves small-signal amplification, narrow-band filtering, integration of the mean-square signal for a sufficient period of time (10x the lowest period for reasonable validity), and repeated measurements under carefully-controlled conditions. On-line testing under production conditions is even more difficult; it will be discussed shortly.

Though acutal noise vs. frequency plots for devices do not have ideal shapes, there are certain approximate distributions that recur frequently over portions of the spectrum; they are: "white" noise (uniform frequency distribution, i.e., e_n = constant or i_n = constant), and "1/f" noise ($e_n{}^2$ or $i_n{}^2$ inversely proportional to frequency, -6dB per octave, or e_n or i_n inversely proportional to the square-root of frequency, -3dB per octave). Over a band of frequencies, f_H to f_L, the results of integrating to obtain rms noise are:

*You will find no consistent usage in the industry. Analog Devices generally uses the "root" form, $\mu V/\sqrt{Hz}$ or $pA/\sqrt{Hz}$. Be sure to check the scale calibration of any plots you may be dealing with.

White noise (e_n constant):

$$E_n = \sqrt{\int_{f_L}^{f_H} e_n{}^2 \, df} = \sqrt{e_n{}^2 \int_{f_L}^{f_H} df} = e_n\sqrt{f_H - f_L} \cong e_n\sqrt{f_H} \qquad (3)$$

1/f noise:

$$E_n = \sqrt{\int_{f_L}^{f_H} e_n{}^2(f_1)\frac{f_1}{f}\, df} = e_n(f_1)\sqrt{f_1}\sqrt{\int_{f_L}^{f_H}\frac{df}{f}} = e_n(f_1)\sqrt{f_1}\,\sqrt{\ln(f_H/f_L)} \qquad (4)$$

Here is an example: if the noise output of a given amplifier configuration is approximately "white" from 100Hz to 10kHz, with $e_n = 0.1\mu V/\sqrt{Hz}$, and "1/f" from 1Hz to 100Hz, with $e_n\,(10Hz) = 0.32\mu V/\sqrt{Hz}$, we can use root sum-of-squares summation of (3) and (4) to find the total rms noise in the band 1Hz to 10kHz:*

$$E_n{}^2 = (0.1)^2(10)^4 + (0.32)^2(10)\ln(100/1) = 100 + \ln(100) = 105\mu V^2$$

$$E_n = \sqrt{105} = 10.2\mu V \text{ rms}$$

First-order RC high-pass and low-pass filters are ordinarily used to limit bandwidth for measurements. Since their response is tapered to 6dB per octave, rather than "rectangular," they pass some out-of-band noise and attenuate some in-band noise, which may provide a value of measured rms noise that would differ from the results of measuring with a "perfect" filter. For white noise, a low-pass filter will have an equivalent cutoff frequency of 1/4RC, instead of $1/2\pi RC$; the same is true for a high-pass filter at the low end, though f_L for broadband white noise is unimportant. For 1/f noise, the low-pass cutoff frequency and the high-pass cutoff frequency are both very close to $1/2\pi RC$.

"White" noise characterizes ideal resistors and junctions; for resistors, "Johnson" noise has the values, $e_n = \sqrt{4kTR} \cong 0.129\mu V/\sqrt{Hz}$ for R = 1MΩ @ 300°K, and $i_n = \sqrt{4kT/R} \cong 0.129pA/\sqrt{Hz}$, where k is Boltzmann's constant = 1.380622 x 10^{-23}J/°K, T is absolute temperature, and R is the resistance. For junctions, the shot noise, $i_n = \sqrt{2qI} = 5.7 \times 10^{-4}\sqrt{I}$ picoamperes/$\sqrt{Hz}$, where I is the current flowing through the junction, in pA, and q is the charge on an electron, 1.6021917 x 10^{-19}C. This formula can be used to compute the limiting low-frequency current noise of a FET-input op amp, if I is the input leakage current. For example, if I = 10pA (maximum specification for AD514L), $i_n = 5.7 \times 10^{-4}\sqrt{10} = 1.8 \times 10^{-3} pA/\sqrt{Hz}$, or $1.8fA/\sqrt{Hz}$.

In the frequency range below 100Hz, most amplifiers exhibit another noise component that dominates the Johnson and shot components and becomes the chief source of error at those frequencies. Dubbed "flicker noise," or "pink" noise, its power

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*A powerful graphical technique can be found in *Analog Dialogue*, Volume 3, No. 1 (1969), pp. 11–12.