Ask the Applications Engineer—7

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OP-AMP ISSUES—NOISE

Q. What should I know about op-amp noise?

A. First, we must note the distinction between noise generated in the op amp and its circuit components and *interference*, or unwanted signals and noise arriving as voltage or current at any of the amplifier's terminals or induced in its associated circuitry.

Interference can appear as spikes, steps, sine waves, or random noise, and it can come from *anywhere*: machinery, nearby power lines, r-f transmitters and receivers, computers, or even circuitry within the same equipment (for example, digital circuits or switching-type power supplies). Understanding it, preventing its appearance in your circuit's neighborhood, finding how it got in, and rooting it out, or finding a way to live with it is a big subject. It's been treated in these pages in the past; those, and a few additional references, are mentioned in the Bibliography.

If all interference could be eliminated, there would still be random noise associated with the operational amplifier and its resistive circuits. It constitutes the ultimate limitation on the amplifier's resolution. That's the topic we'll begin to discuss here.

Q. O.K. Tell me about random noise in op amps. Where does it come from?

A. Noise appearing at the amplifier's output is usually measured as a voltage. But it is generated by both voltage- and current sources. All internal sources are generally *referred to the input*, i.e., treated as uncorrelated—or *independent*—random noise generators (see next question) in series or parallel with the inputs of an ideal noisefree amplifier: We consider 3 primary contributors to noise:

- a noise *voltage* generator (like offset voltage, usually shown in series with the noninverting input)
- two noise-*current* generators pumping currents out through the two differential-input terminals (like bias current).
- If there are any resistors in the op-amp circuit, they too generate noise; it can be considered as coming from either current sources or voltage sources (whichever is more convenient to deal with in a given circuit).

Op-amp voltage noise may be as low as 3 $nV/\sqrt{Hz}$. Voltage noise is the noise specification that is more usually emphasized, but, if impedance levels are high, current noise is often the limiting factor in system noise performance. That is analogous to offsets, where offset voltage often bears the blame for output offset, but bias current is the actual guilty party. Bipolar op-amps have traditionally had less *voltage* noise than FET ones, but have paid for this advantage with substantially greater *current* noise—today, FET op-amps, while retaining their low current noise, can approach bipolar voltage-noise performance.

Q. Hold it! 3 $nV/\sqrt{Hz}$? Where does $\sqrt{Hz}$ come from? What does it mean?

A. Let's talk about random noise. Many noise sources are, for practical purposes (i.e., within the bandwidths with which the designer is concerned), both white and Gaussian. White noise is noise whose power within a given bandwidth is independent of frequency. Gaussian noise is noise where the probability of a particular amplitude, X, follows a Gaussian distribution. Gaussian noise has the property that when the rms values of noise from two or more such sources are added, provided that the noise sources are uncorrelated (i.e., one noise signal cannot be transformed into the other), the resulting noise is not their arithmetic sum but the root of the sum-of-their-squares (RSS).* The RSS sum of three noise sources, V_1, V_2, and V_3, is

$$V_O = \sqrt{V_1^2 + V_2^2 + V_3^2}$$

Since the different frequency components of a noise signal are uncorrelated, a consequence of RSS summation is that if the white noise in a brick-wall bandwidth of Δf is V, then the noise in a bandwidth of 2 Δf is $\sqrt{V^2 + V^2} = \sqrt{2}\,V$. More generally, if we multiply the bandwidth by a factor K, then we multiply the noise by a factor $\sqrt{K}$. The function defining the rms value of noise in a Δf = 1 Hz bandwidth anywhere in the frequency range is called the (voltage or current) *spectral density function*, specified in $nV/\sqrt{Hz}$ or $pA/\sqrt{Hz}$. For white noise, the spectral density is constant; it is multiplied by the square root of the bandwidth to obtain the total rms noise.

A useful consequence of RSS summation is that if two noise sources are contributing to the noise of a system, and one is more than 3 or 4 times the other, the smaller is often ignored, since

$$\sqrt{4^2} = \sqrt{16} = 4, \text{ while } \sqrt{4^2 + 1^2} = \sqrt{17} = 4.12$$

[difference less than 3%, or 0.26 dB]

$$\sqrt{3^2} = \sqrt{9} = 3, \text{ while } \sqrt{3^2 + 1^2} = \sqrt{10} = 3.16$$

[difference less than 6%, or 0.5 dB]

The source of the higher noise has become the *dominant* source.

Q. O.K. How about current noise?

A. The current noise of simple (i.e. not bias-current-compensated) bipolar and JFET op-amps is usually within 1 or 2 dB of the Schottky noise (sometimes called the "shot noise") of the bias current; it is not always specified on data sheets. Schottky noise is current noise due to random distribution of charge carriers in the current flow through a junction. The Schottky noise current, I_n, in a bandwidth, B, when a current, I, is flowing is obtained from the formula

$$I_n = \sqrt{2I\,qB}$$

Where q is the electron charge (1.6×10^{-19} C). Note that $\sqrt{2I\,q}$ is the spectral density, and that the noise is white.

This tells us that the current noise spectral density of simple bipolar transistor op-amps will be of the order of 250 $fA/\sqrt{Hz}$, for I_b = 200 nA, and does not vary much with temperature—and that the current noise of JFET input op-amps, while lower (4 $fA/\sqrt{Hz}$ at I_b = 50 pA), will double for every 20°C chip temperature increase, since JFET op-amps' bias currents double for every 10°C increase.

Bias-compensated op-amps have much higher current noise than one can predict from their input currents. The reason is that their net bias current is the *difference* between the base current of the input transistor and the compensating current source, while the noise current is derived from the RSS *sum* of the noise currents.

[*Note the implication that noise *power* adds linearly (sum of squares).]

Traditional voltage-feedback op-amps with balanced inputs almost always have equal (though uncorrelated) current noise on both their inverting and non-inverting inputs. Current-feedback, or transimpedance, op-amps, which have different input structures at these two inputs, do not. Their data sheets must be consulted for details of the noise on the two inputs.

The noise of op-amps is Gaussian with constant spectral density, or "white", over a wide range of frequencies, but as frequency decreases the spectral density starts to rise at 3 dB/octave. This low-frequency noise characteristic is known as "$1/f$ noise" since the noise *power* spectral density goes inversely with frequency. It has a −1 slope on a log plot (the noise *voltage* (or *current*) $1/\sqrt{f}$ spectral density slopes at $-1/2$). The frequency at which an extrapolated −3 dB/octave spectral density line intersects the mid-frequency constant spectral density value is known as the "1/f corner frequency" and is a figure of merit for the amplifier. Early monolithic IC op-amps had 1/f corners at over 500 Hz, but today values of 20–50 Hz are usual, and the best amplifiers (such as the AD-OP27 and the AD-OP37) have corner frequencies as low as 2.7 Hz. $1/f$ noise has equal increments for frequency intervals having equal ratios, i.e., per *octave* or per *decade*.

Q: Why don't you publish a noise figure?

A: The noise figure (NF) of an amplifier (expressed in dB) is a measure of the ratio of the amplifier noise to the thermal noise of the source resistance.

$$V_n = 20 \log \{ [V_n(\text{amp}) + V_n(\text{source})]/V_n(\text{source})\}$$

It is a useful concept for r-f amplifiers, which are almost always used with the same source resistance driving them (usually 50 Ω or 75 Ω), but it would be misleading when applied to op amps, since they are used in many different applications with widely varying source impedances (which may or may not be resistive).

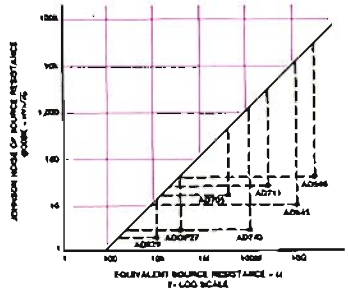
Q: What difference does the source impedance make?

A: At temperatures above absolute zero all resistances are noise sources; their noise increases with resistance, temperature, and bandwidth (we'll discuss basic resistance noise, or *Johnson noise*, in a moment). *Reactances* don't generate noise, but noise currents through them will develop noise voltages.

If we drive an op-amp from a source resistance, the equivalent noise input will be the RSS sum of the amplifier's noise voltage, the voltage generated by the source resistance, and the voltage caused by the amplifier's I_n flowing through the source impedance. For very low source resistance, the noise generated by the source resistance and amplifier current noise would contribute insignificantly to the total. In this case, the noise at the input will effectively be just the voltage noise of the op-amp.

If the source resistance is higher, the Johnson noise of the source resistance may dominate both the op-amp voltage noise and the voltage due to the current noise; but it's worth noting that, since the Johnson noise only increases with the square root of the resistance, while the noise voltage due to the current noise is directly proportional to the input impedance, the amplifier's current noise will always dominate for a high enough value of input impedance. When an amplifier's voltage and current noise are high enough, there may be no value of input resistance for which Johnson noise dominates.

This is demonstrated by the figure below, which compares voltage and current noise noise for several Analog Devices op amp types, for a range of source-resistance values. The diagonal line plots vertically the Johnson noise associated with resistances on the horizontal scale. Let's read the chart for the ADOP27: The horizontal line indicates the ADOP27's voltage noise level of about 3 nV/$\sqrt{\text{Hz}}$ is equivalent to a source resistance of less than about 500 Ω. Noise will not be reduced by (say) a 100-Ω source impedance, but it will be increased by a 2-kΩ source impedance. The vertical line for the ADOP27 indicates that, for source resistances above about 100 kΩ, the noise voltage produced by amplifier's current noise will exceed that contributed by the source resistance; it has become the dominant source.



Remember that any resistance in the non-inverting input will have Johnson noise and will also convert current noise to a noise voltage; and Johnson noise in feedback resistors can be significant in high-resistance circuits. All potential noise sources must be considered when evaluating op amp performance.

Q. You were going to tell me about Johnson noise.

A. At temperatures above absolute zero, all resistances have noise due to thermal movement of charge carriers. This is called Johnson noise. The phenomenon is sometimes used to measure cryogenic temperatures. The voltage and current noise in a resistance of R ohms, for a bandwidth of B Hz, at a temperature of T kelvins, are given by:

$$V_n = \sqrt{4kTRB} \text{ and } I_n = \sqrt{4kTB/R}$$

Where k is Boltzmann's Constant (1.38×10^{-23} J/K). A handy rule of thumb is that a 1-kΩ resistor has noise of 4 nV/$\sqrt{\text{Hz}}$ at room temperature.

All resistors in a circuit generate noise, and its effect must always be considered. In practice, only resistors in the input(s) and, perhaps, feedback, of high-gain, front-end circuitry are likely to have an appreciable effect on total circuit noise.

Noise can be reduced by reducing resistance or bandwidth, but temperature reduction is generally not very helpful unless a resistor can be made very cold—since noise power is proportional to the *absolute* temperature, T = °C + 273°.

(to be continued)

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