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Low Noise Amplifier Selection Guide for Optimal Noise Performance

by Paul Lee

INTRODUCTION

When evaluating an amplifier's performance for a low noise application, one factor to consider is noise, both internal and external. This application note briefly discusses the fundamentals of both internal and external noise and identifies the tradeoffs associated in selecting the optimal amplifier for low noise design.

EXTERNAL NOISE

There is a distinction between internal and external noise sources. External noise can include any external influence, such as external components and electrical/electromagnetic interference. Interference is any unwanted signals arriving as either voltage or current, at any of the amplifier's terminals or induced in its associated circuitry. It can appear as spikes, steps, sine waves, or random noise. Interference can come from anywhere: machinery, nearby power lines, RF transmitters or receivers, computers, or even circuitry within the same equipment (that is, digital circuits or switching-type power supplies). If all interference could be eliminated by careful design and/or layout of the board, there would still be random noise associated with the amplifier and its circuit components.

Noise from surrounding circuit components must be accounted for. At temperatures above absolute zero, all resistances are noise sources, due to thermal movement of charge carriers called Johnson noise or thermal noise. This noise increases with resistance, temperature, and bandwidth. The voltage and current noise is given by the following equations:

$$V_n = \sqrt{4kTBR}$$

$$I_n = \sqrt{\frac{4kTB}{R}}$$

where:
k is Boltzmann's constant (1.38 × 10−23 J/K).
T is the temperature in Kelvin.
B is the bandwidth in Hz.
R is the resistance in Ω.

Typically, a 1 kΩ resistor has a noise of about 4 nV/√Hz at room temperature. For an in-depth analysis, other noise sources of the resistor should be accounted for, such as contact noise, shot noise, and parasitics associated with particular type of resistors. For the purposes of this application note, the resistor noise is limited to Johnson noise as it is proportional to the square root of the resistor value.

Reactances do not generate noise, but noise currents through reactances develop noise voltages as well as the associated parasitics.

Output noise from a circuit can be reduced by reducing the total component resistance or by limiting the circuit bandwidth. However, temperature reduction is generally not very helpful unless a resistor can be made very cold, because noise power is proportional to the absolute temperature,

T(x) in Kelvin = x°C + 273.15°

All resistors in a circuit generate noise, and its effect must always be considered. In practice, only resistors in the input and feedback paths (typically in high gain configurations) are likely to have an appreciable effect on total circuit noise. The noise can be considered as coming from either current sources or voltage sources (whichever is more convenient to deal with in a given circuit).

INTERNAL NOISE

Noise appearing at the amplifier's output is usually measured as a voltage. However, it is generated by both voltage and current sources. All internal sources are generally referred to the input, that is, treated as uncorrelated or independent random noise generators in series or in parallel with the inputs of an ideal noise-free amplifier (see Figure 1). Because these noise sources are considered random and/or exhibit Gaussian distribution behavior, it is important to take care when summing the noise sources as discussed in the Summing the Noise Sources section.

Internal amplifier noise falls into the following categories: input-referred voltage noise, input-referred current noise, shot noise, and, occasionally, popcorn noise (not specified or advertised).

Input-referred voltage noise and input-referred current noise are the most common specifications used for amplifier noise analysis. They are often specified as an input-referred spectral density function or the rms noise contained in Δf = 1 Hz bandwidth and usually given in terms of pA/√Hz (for current noise) or nV/√Hz (for voltage noise). The /√Hz is needed because the noise power adds with (is cumulative over) bandwidth (Hz) or the voltage noise density adds with square root of the bandwidth (√Hz).

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FOUR TYPES OF INTERNAL NOISE

This section describes input-referred voltage noise, input-referred current noise, flicker noise, and popcorn noise.

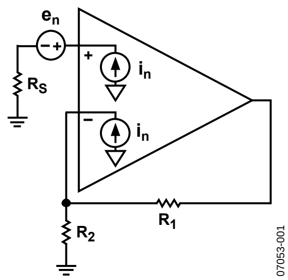

Figure 1. Op Amp Noise Model

INPUT-REFERRED VOLTAGE NOISE

Input-referred voltage noise (e_n) is typically viewed as a noise voltage generator.

Voltage noise is the noise specification that is usually emphasized; however, if impedance levels are high, current noise is often the limiting factor in system noise performance. It is analogous to offsets, where input offset voltage often bears the blame for output offset, when in reality the bias current causes the output offset where input impedances are high.

Note the following points about input-referred voltage noise:

- Op amp voltage noise can be lower than 1 nV/√Hz for the highest performance amplifiers.
- Although bipolar op amps traditionally have less voltage noise than FET op amps, they also have substantially greater current noise.
- Bipolar amplifier noise characteristics are dependent on the quiescent current.
- Present day FET op amps are capable of obtaining both low current noise and voltage noise similar to bipolar amplifier performance, though not as low as the best bipolar input amplifiers.
- Traditional voltage feedback op amps with balanced inputs usually have equal (correlated and uncorrelated) current noise on both their inverting and noninverting inputs.
- Many amplifiers, especially those amps with input bias current cancellation circuits, have considerably larger correlated than uncorrelated noise components. Overall, noise can be improved by adding an impedance-balancing resistor (matching impedances on both positive and negative input pins), contrary to popular assumption.
- Some low noise FET op amps also have large correlated noise components, due to noise in the tail current coupling into the inputs via the gate source capacitance.

INPUT-REFERRED CURRENT NOISE

Input-referred current noise (i_n) is typically seen as two noise current generators pumping currents out through the two differential input terminals.

The current noise of a simple bipolar and JFET op amp is usually within 1 dB or 2 dB of the Schottky noise (sometimes called the shot noise) of the bias current. This specification is not always listed on data sheets. Schottky noise is a current noise due to random distribution of charge carriers in the current flow through a junction. The Schottky noise current, i_n, is obtained from the formula

$$i_n = \sqrt{2 I_B q B}$$

where:
I_B is the bias current.
q is the electron charge (1.6×10^{-19} C).
B is the bandwidth.

Note the following points regarding input-referred noise:

- The current noise of typical bipolar transistor op amps, such as the OP27, is about 400 fA/√Hz, where I_B = 10 nA, and does not vary much with temperature except for bias, current-compensated amplifiers.
- The current noise of JFET input op amps, while lower, (such as the AD8610: 5 fA/√Hz at I_B = 10 pA), doubles for every 20°C chip temperature increase, because JFET op amp bias currents double for every 10°C increase.

FLICKER NOISE

The noise of op amps is Gaussian with constant spectral density (white noise), over a wide range of frequencies, but as frequency decreases, the spectral density starts to rise because of the fabrication process, the IC device layout, and the device type at a rate of about

- 3 dB per octave for CMOS amplifiers.
- 3.5 dB to 4.5 dB per octave for bipolar amplifiers.
- Up to 5 dB per octave for JFET amplifiers.

This low frequency noise characteristic is known as flicker noise or 1/f noise because the noise power spectral density goes inversely with frequency (1/f). It has a −1 slope on a log plot. The frequency at which an extrapolated −3 dB per octave (for CMOS-type amplifier) spectral density line intersects the broadband constant spectral density value is known as the 1/f corner frequency and is a figure of merit for the amplifier. Even though bipolar and JFET amplifiers have higher slope rate than CMOS amplifiers, their 1/f corner frequency is lower.

POPCORN NOISE

Popcorn noise, or random noise, is an abrupt shift in offset voltage or current lasting for several milliseconds with amplitude from several μV to hundreds of μV. This burst or pop is very random. Low temperatures and high source resistances usually produce the most favorable conditions for popcorn noise. Although the root cause of popcorn noise is not absolute, both metallic contamination and internal or surface defects in the silicon lattice can cause popcorn or burst noise in ICs. Although considerable work has been done to reduce the sources of popcorn noise in modern wafer fabrication, it cannot be eliminated.

SUMMING THE NOISE SOURCES

Noise sources are 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 (that is, one noise signal cannot be transformed into the other), the resulting noise is not their arithmetic sum, but the square root of the sum of their squares.

$$V_{n,\ Total} = \sqrt{(e_n)^2 + (R_S \times\ i_n)^2 + V_n\ (R_{TH})^2}$$

where:
e_n is input-referred-voltage-noise.
i_n is input-referred current noise.
R_S is an equivalent source or input resistance to the amplifier.
$V_n\ (R_{TH})$ is voltage noise of Thevenin equivalent resistance from external circuitry.

Any resistance in the noninverting input has Johnson noise and converts current noise to a voltage noise. Johnson noise in feedback resistors can be significant in high resistance circuits.

SELECTING LOW NOISE OP AMP

If an op amp is driven with a source resistance, the equivalent noise input becomes the square root of the sum of the squares of

- the amplifier's voltage noise,
- the voltage generated by the source resistance, and
- the voltage caused by the amplifiers current noise flowing through the source impedance.

For very low source resistances, the noise generated by the source resistance and amplifier current noise contribute insignificantly to the total. In this case, the noise at the input is effectively only the voltage noise of the op amp.

If the source resistance is high, the Johnson noise of the source resistance may dominate both the op amp voltage noise and the voltage due to the current noise. However, it is 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 always dominates 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.

An amplifier can be selected where its noise contribution is negligible compared to the source resistance by using a figure of merit, $R_{S,OP}$, of an op amp. It can be calculated by using an amplifier's noise specification.

$$R_{S,OP} = \frac{e_n}{i_n}$$

where:
e_n is input-referred voltage noise.
i_n is input-referred current noise.

Figure 2 shows a comparison of the voltage noise density of a number of Analog Devices, Inc., high voltage (up to 44 V) op amps vs. $R_{S,OP}$ at 1 kHz. The diagonal line plots the Johnson noise associated with resistance.

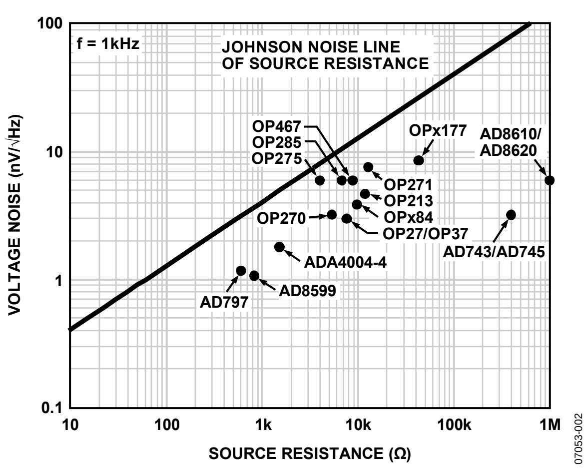

Figure 2. Voltage Noise vs. ($R_{S,OP}$)

Similar types of graph can be constructed for a chosen frequency from the data in the op amp data sheet (see Table 1). For example, consider the AD8599. This device has an input-referred voltage noise of about 1 nV/√Hz and an input-referred current noise of 1.5 pA/√Hz at 1 kHz. The $R_{S,OP}$ is about 823 Ω at 1 kHz. In addition, note the following:

- The Johnson noise associated with this device is equivalent to a source resistor of about 61 Ω (see Figure 2).
- For a source resistance above about 823 Ω, the noise voltage produced by the amplifier's current noise exceeds that contributed by the source resistance; the amplifier's current noise becomes the dominant noise source.

To use the graph (see Figure 3), follow Step 1 through Step 4.

1. Typically, the source resistances are known (such as sensor impedances). If the resistances are not know, calculate them from the surrounding or preceding circuit components.
2. Locate the given source resistance, such as 1 kΩ, on the Johnson noise line.
3. Create a horizontal line from the point located in Step 2 to the right of the plot.
4. Create a line down and to the left from the point located in Step 2). Do this by decreasing one decade of voltage noise per one decade of resistance.

Any amplifiers below and to the right of the lines are good low noise op amps for the design as highlighted in the shade of gray in Figure 3.

For the example shown in Figure 3, the following devices are good candidates for the design: AD8599, AD797, ADA4004-4, OP270, OP27/OP37, AD743/AD745, and OP184.

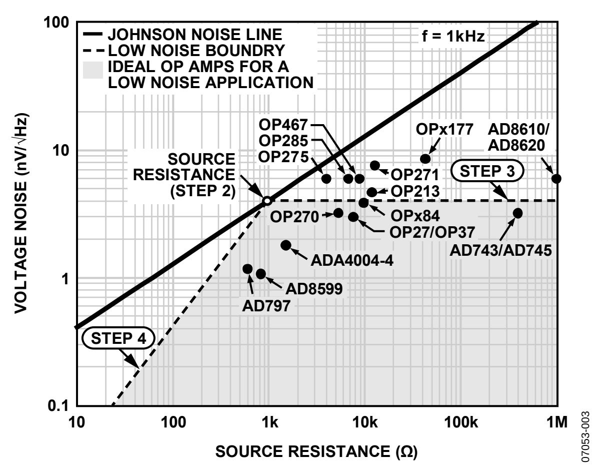

Figure 3. Using the Graph

CONCLUSION

Consider all potential noise sources when evaluating an amplifiers noise performance for low noise design.

In summary, reduce or eliminate interference signals by

- Proper layout techniques to reduce parasitics
- Proper ground techniques, such as isolating digital and analog ground
- Proper shielding

In regards to resistive noise sources

- Restrict bandwidth to only what is necessary
- Reduce resistor value where possible
- Use low noise resistors, such as bulk metal foil, wirewound, and metal film technology resistors

The key noise contribution of an op amp is dependent on source resistance as follows:

- $R_S > R_{S,OP}$; input-referred current noise dominates
- $R_S = R_{S,OP}$; amplifier noise is negligible; resistor noise dominates
- $R_S < R_{S,OP}$; input-referred voltage noise dominates

Reduce the number of resistive noise sources where possible.

Use Figure 2 and Table 1 to assist with the selection of an Analog Devices low noise amplifier using the criteria described in this application note.

Table 1.

ANALOG DEVICES LOW NOISE AMPLIFIER SELECTION TABLE

PART NUMBER	V_{SY} (V)	V_{OS} MAX (µV)	TCV_{OS} (µV/°C)	GBP (MHz)	SLEW RATE (V/µs)	I_{SY}/AMP MAX (mA)	e_N @ 1kHz (nV/√Hz)	I_N (pA/√Hz)	$R_{S, OP}$ @ 1kHz (Ω)	1/f CORNER (Hz)	I_B MAX (nA)	I_{OUT} (mA)	CMRR MIN (dB)	PSRR MIN (dB)	NUMBER OF AMPS
AD797	10 TO 36	40	0.2	8	20	10.5	0.9	2	600	60	900	50	120	120	1
AD8599	9 TO 36	120	0.8	10	15	5.7	1	1.5	823	9	180	50	120	120	2
ADA4004-4	10 TO 36	140	0.7	12	2.7	1.7	1.8	1.2	1500	5	85	10	110	110	4
AD8676	10 TO 36	50	0.2	10	2.5	2.7	2.8	0.3	—	10	2	20	105	106	2
AD8675	10 TO 36	75	0.2	10	2.5	2.7	2.8	0.3	—	10	2	20	105	120	1
OP27	8 TO 44	25	0.2	8	2.8	5.7	3	0.4	7500	2.7	40	25	114	100	1
OP37	8 TO 44	25	0.2	12	17	5.7	3	0.4	7500	2.7	40	25	114	100	1
OP270/ OP470	9 TO 36	75	0.2	5	2.4	3.25	3.2	0.6	5333	5	20	15	106	110	1/ 2
AD743	9.6 TO 36	1000	2	4.5	2.8	10	3.2	0.0069	400000	50	0.4	40	80	90	1
AD745	9.6 TO 36	500	2	20	12.5	10	3.2	0.0069	400000	50	0.25	40	90	88	1
AD8671/ AD8672/ AD8674	10 TO 36	75	0.3	10	4	3.5	3.8	0.3	—	10	12	20	100	103	1/2/4
OP184/ OP284/ OP484	3 TO 36	65	0.2	4.25	4	2	3.9	0.4	9750	10	450	10	86	90	1/ 2/ 4
OP113/ OP213/ OP413	4 TO 36	75	0.2	3.4	1.2	3	4.7	0.4	11750	10	600	40	100	103	1/ 2/ 4
SSM2135	4 TO 36	2000		3.5	0.9	3	5.2	0.5	10400	3	750	30	87	90	2
OP285	9 TO 44	250	1	9	22	2.5	6	0.9	6667	125	350	30	80	85	2
AD8610/ AD8620	10 TO 27	100	0.5	25	50	4	6	0.005	1200000	1000	0.01	30	90	100	1/ 2
OP275	9 TO 44	1000	2	9	22	2.5	6	1.5	4000	2.24	350	30	80	85	2
OP467	9 TO 36	500	3.5	28	170	2.5	6	0.8	8750	8	600	40	80	96	4
OP471	9 TO 36	800	1	6.5	8	2.75	6.5	0.4	16250	5	25	10	105	105	4
OP271	9 TO 36	200	0.4	5	8.5	3.25	7.6	0.6	12667	40	20	20	106	106	2
OP1177/ OP2177/ OP4177	5 TO 36	60	0.2	1.3	0.7	0.5	7.9	0.2	42500	10	2	10	120	120	1/ 2/ 4

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REFERENCES

Analog Devices, Inc. "Mixed Signal Circuit Techniques." Application Note AN-280.

Barrow, J., and Paul Brokaw. 1989. "Grounding for Low- and High-Frequency Circuits." Analog Dialogue. Analog Devices, Inc. (23-3).

Bennett, W. R. 1960. *Electrical Noise*. New York: McGraw-Hill.

Bowers, Derek F. 1989. "Minimizing Noise in Analog Bipolar Circuit Design." IEEE Press.

Brockman, Don and Arnold Williams. "Ground Rules for High-Speed Circuits." Application Note AN-214. Analog Devices, Inc.

Brokaw, Paul. "An IC Amplifier User's Guide to Decoupling, Grounding, and Making Things Go Right for a Change." Application Note AN-202. Analog Devices, Inc.

Brokaw, Paul and Jeff Barrow, "Grounding for Low- and High-Frequency Circuits." Application Note AN-345. Analog Devices, Inc.

Bryant, James Bryant and Lew Counts. 1990. "Op Amp Issues–Noise " Analog Dialogue. Analog Devices Inc. (24–2).

Freeman, J. J. 1958. *Principles of Noise*. New York: John Wiley & Sons, Inc.

Gupta, Madhu S., ed., 1977. *Electrical Noise: Fundamentals & Sources*. New York: IEEE Press. Collection of classical reprints.

Johnson, J. B. 1928. "Thermal Agitation of Electricity in Conductors" (Physical Review 32): 97–109.

Motchenbacher, C. D., and J. A. Connelly. 1993. *Low-Noise Electronic Design*. New York: John Wiley & Sons, Inc.

Nyquist, H. 1928. "Thermal Agitation of Electric Charge in Conductors" (Physical Review 32): 110–113.

Rice, S.O. 1944. "Math Analysis for Random Noise" *Bell System Technical Journal* (July): 282–332.

Rich, Alan. 1982. "Understanding Interference-Type Noise." Analog Dialogue. Analog Devices Inc. (16–3).

Rich, Alan. 1983. "Shielding and Guarding." Analog Dialogue. Analog Devices Inc. (17–1).

Ryan, Al and Tim Scranton. 1984. "DC Amplifier Noise Revisited." Analog Dialogue. Analog Devices, Inc. (18–1).

Schottky, W. 1926. "Small-Shot Effect and Flicker Effect." (Phys. Rev. 28): 74–103.

Van Der Ziel, A. 1954. *Noise*. Englewood Cliffs, NJ: Prentice-Hall, Inc.

NOTES