Keywords: low noise amplifiers, strain-gauge, bipolar, CMOS, JFET, noise density

Sep 20, 2005

APPLICATION NOTE 3642

Choosing a Low-Noise Amplifier

Abstract: This article examines key parameters that contribute to amplifier noise. It explains how amplifier design, specifically the choice of bipolar, JFET-input, or CMOS-input design, affects noise. The note also explains how to select a low-noise amplifier for low-frequency analog applications such as buffering data converters, amplifying strain-gauge signals, and preamplifying microphone outputs. The CMOS-input based amplifier, MAX4475, illustrates the benefits of using this newer amplifier design for many lower frequency analog applications.

A discussion of low-noise amplifiers usually implies RF/wireless applications. But noise is also a critical consideration for lower frequency analog applications like buffering data converters, amplifying strain-gauge signals, and preamplifying microphone outputs. To select an appropriate amplifier, an engineer must first understand the noise parameters for a particular application and then determine whether an amplifier is indeed low-noise. Additionally, it is imperative that the designer understand how the type of IC—bipolar, JFET-input, or CMOS-input—affects noise parameters.

Noise Parameters

Although many parameters specify an amplifier's noise performance, the two most important factors are voltage noise and current noise. Voltage noise is the voltage fluctuations at the input of an otherwise noise-free amplifier with shorted inputs. Current noise is the current fluctuations at the input of an otherwise noise-free amplifier with open inputs.

The typical figure of merit for amplifier noise is noise density, also called spot noise. Voltage-noise density is specified in nV/$\sqrt{Hz}$, while current-noise density is usually shown in units of pA/$\sqrt{Hz}$. These values are provided in all low-noise amplifier data sheets, and are usually specified at two frequencies: at less than 200Hz for the flicker-noise component, and at 1kHz for the flat-band component. For simplicity, these measurements are referred to the amplifier inputs to remove the need to account for the amplifier's gain.

Figure 1 shows a typical curve for voltage-noise density vs. frequency. The noise curve is dependent on two main noise components: flicker noise and shot noise. Flicker noise, the random noise intrinsic to all linear devices, is known as 1/f noise. Its amplitude is inversely proportional to frequency. Flicker noise is usually the dominant noise source at frequencies less than 200Hz, as shown in Figure 1. The 1/f corner frequency is the frequency above which the noise amplitude is approximately flat and independent of frequency. Shot noise, the white noise caused by current fluctuations across a forward-biased pn-junction, is present in this frequency range. Note that the 1/f corner frequency for the voltage noise may be different from the 1/f corner frequency for the current noise.

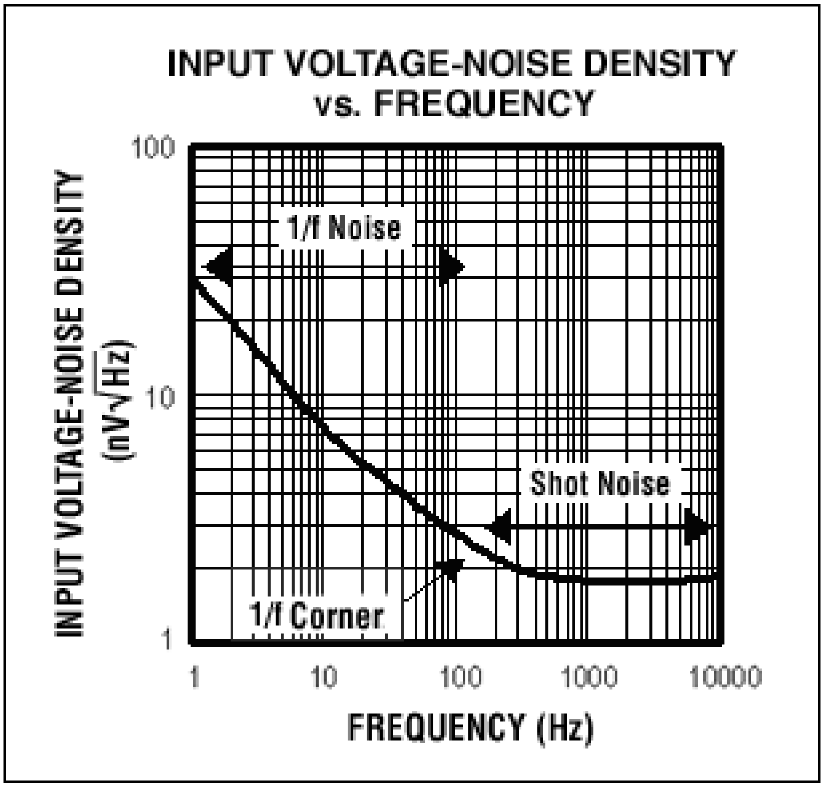

Figure 1. A typical curve for voltage-noise density vs. frequency is dependent on two main noise components: flicker noise and shot noise. Flicker noise, or 1/f noise, is inversely proportional to frequency and is usually the dominant noise source at frequencies less than 200Hz.

An amplifier circuit's total noise depends on the amplifier itself, external circuit impedance, gain, circuit bandwidth, and ambient temperature. The thermal noise from the circuit's external resistors is also part of the total noise calculation. **Figure 2** shows an example of an amplifier and its associated noise components.

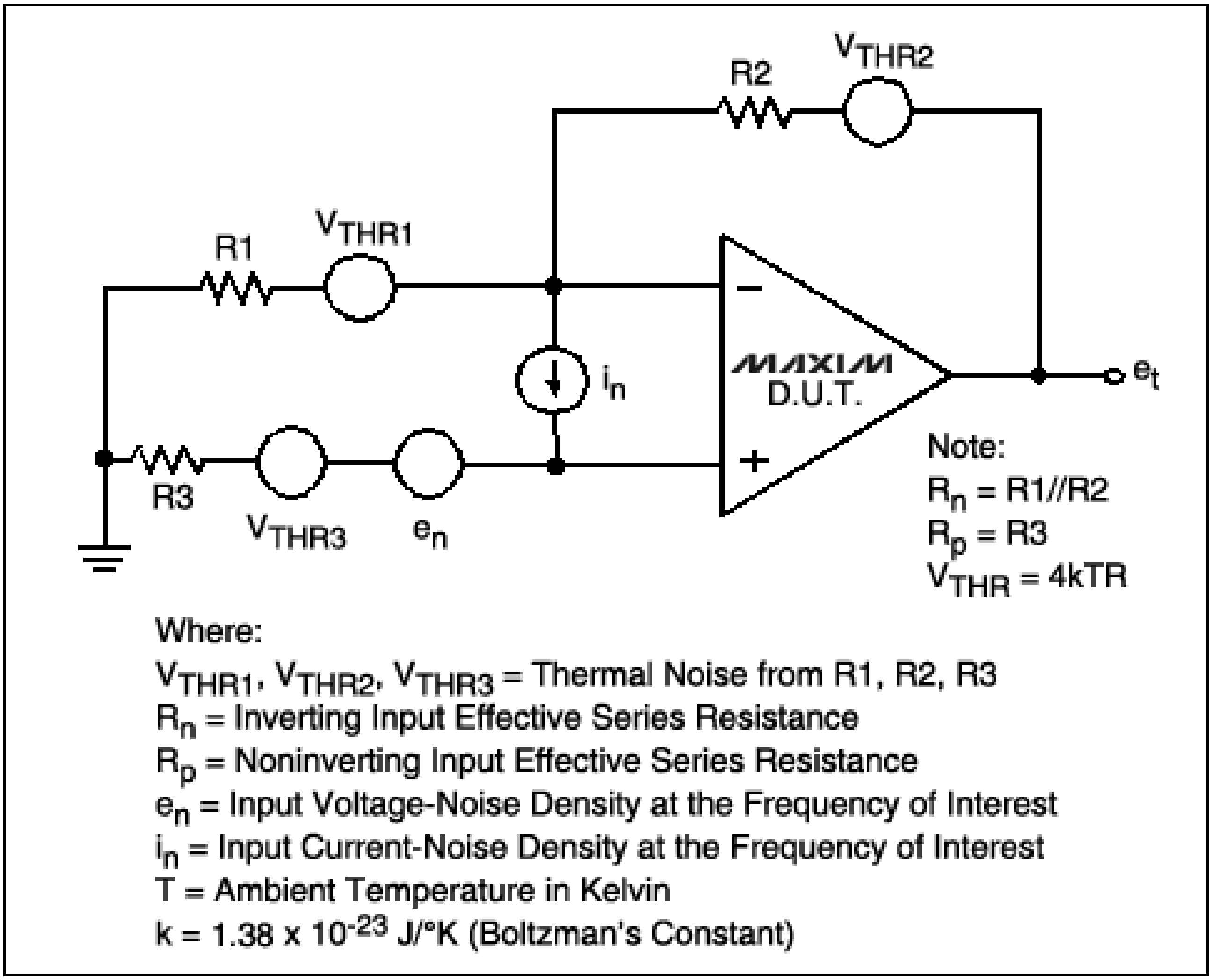

Figure 2. The amplifier circuit's source impedance determines the primary noise term. As source impedance increases, current noise dominates.

Calculating Total Noise

The standard expression for an op amp's total input-referred noise at a given frequency is:

$$e_t = \sqrt{e_n^2 + (R_p + R_n)^2 i_n^2 + 4kT(R_p + R_n)}$$

where:
R_n = Inverting input effective series resistance
R_p = Noninverting input effective series resistance
e_n = Input voltage-noise density at the frequency of interest
i_n = Input current-noise density at the frequency of interest
T = Ambient temperature in Kelvin (°K)
k = 1.38 x 10^{-23} J/°K (Boltzman's constant).

Equation 1 is the noise at a given frequency as a function of bandwidth. To calculate the total noise, multiply et, which is in nV/$\sqrt{Hz}$, by the square root of the bandwidth of interest. For example, if the amplifier circuit's bandwidth ranges from 100Hz to 1kHz, the following expression gives the total noise over the bandwidth:

$$V_t = e_t \cdot \sqrt{(1000 - 100)}$$

The above example shows how to calculate the total noise when the voltage noise and current noise do not vary over the bandwidth. (This usually occurs when the lower end of the amplifier circuit's bandwidth is above the op amp's 1/f frequency for both the voltage and the current noise.) If the voltage noise and current noise do vary over the bandwidth, then the total-noise calculation is more involved.

Based on Equation 1 and Figure 2, it is easy to see the impact of the circuit's source impedance on the noise contributions. Voltage noise is the primary noise contributor in low source-impedance systems. As the equivalent source impedance increases, resistor noise becomes the dominant term, eventually making the amplifier's voltage-noise contribution negligible. As the source impedance increases further, current noise dominates.

The Effect of Amplifier Design on Noise Performance

Noise performance is a function of the amplifier design. The three common designs for low-noise amplifiers are bipolar, JFET-input, and CMOS-input. While each design can provide low-noise performance, their performances are not equal.

Bipolar Amplifiers

Bipolar amplifiers have traditionally been the most common low-noise amplifiers. Low-noise bipolar amplifiers such as the MAX410 offer very low-input voltage-noise density (1.8nV/$\sqrt{Hz}$) with a relatively high-input current-noise density (1.2pA/$\sqrt{Hz}$). Unity-gain bandwidths are typically less than 30MHz for these amplifiers.

To ensure low voltage noise from a bipolar op amp, IC designers set up high collector currents in the input stage. This is because voltage noise is inversely proportional to the square root of the input-stage collector current. Op-amp current noise is, however, proportional to the square root of the input-stage collector current. Therefore, the external feedback and source resistance must be minimized to achieve good noise performance. Note that the input-bias current is proportional to the input-stage collector current. It may thus be necessary to minimize the source resistance to minimize the offset voltage from bias current.

A bipolar amplifier's voltage noise usually dominates when its equivalent source resistance is less than 200Ω. Large input-bias current, coupled with relatively large current noise, make bipolar amplifiers best suited for only low source-impedance applications.

JFET-Input Amplifiers

The best JFET-input low-noise amplifiers feature ultra-low input-current-noise density (0.5fA/$\sqrt{Hz}$), but a higher input voltage-noise density (greater than 10nV/$\sqrt{Hz}$) compared to bipolar designs. JFET designs allow single-supply operation. Input bias currents of 1pA make JFET amps useful for applications with high-impedance sources. However, JFET-based designs are not the board designer's first choice for low source-impedance applications, due to their larger voltage noise.

CMOS-Input Amplifiers

Newer low-noise amplifier designs with a CMOS input stage offer voltage-noise performance that is comparable to bipolar designs. CMOS-input amplifiers also meet or exceed the current-noise performance of the best JFET-input designs. The MAX4475, for example, has low-input voltage-noise density (4.5nV/$\sqrt{Hz}$), low-input current-noise density (0.5fA/$\sqrt{Hz}$), and ultra-low distortion (0.0002% THD+N) while operated from a single supply. These features make CMOS-input amplifiers an excellent choice for applications that require low distortion and low noise, such as audio preamplifiers. Additionally, the CMOS input stage allows for very low input-bias currents, low offset voltages, and very high input impedances, making these devices well suited for signal conditioning high-impedance sources, such as the photodiode preamplifier circuit shown in **Figure 3**. An output buffer for a 16-bit DAC output is shown in **Figure 4**.

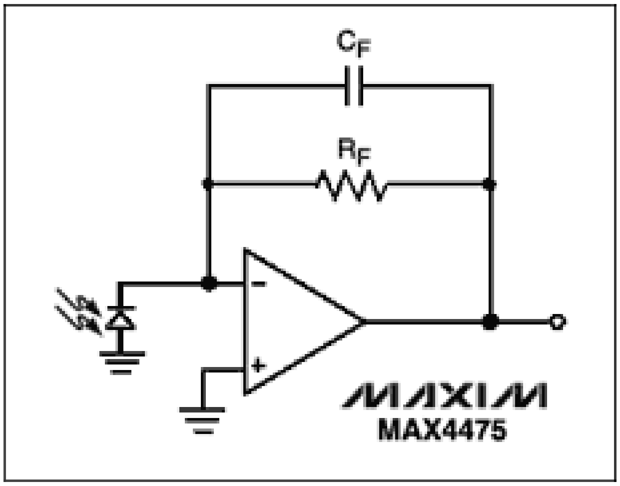

Figure 3. Low-noise amplifiers with a CMOS input stage have very low-input bias currents and offset voltages coupled with very high input impedances. These devices are well suited for signal conditioning high-impedance sources, such as a photodiode preamplifier.

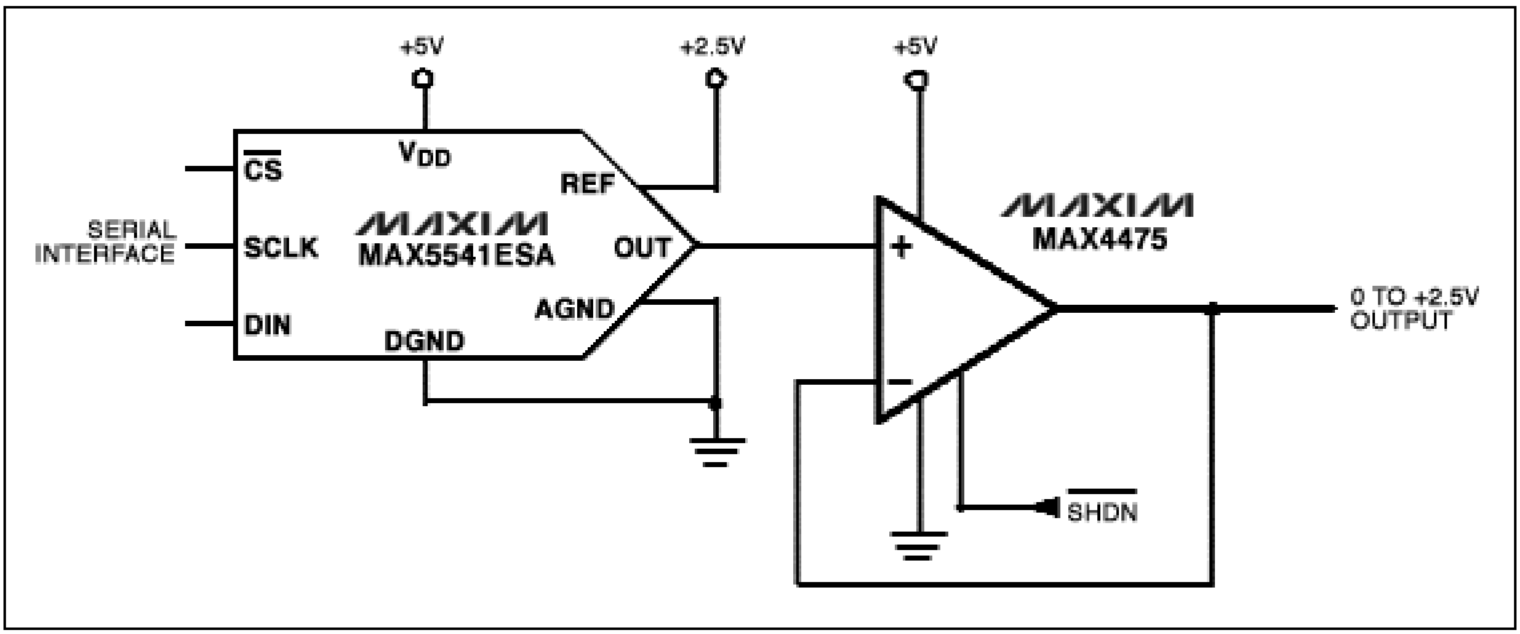

Figure 4. Low-noise performance and low-input bias currents make CMOS-input amplifiers an ideal choice to buffer a 16-bit DAC output.

Conclusion

No single amplifier is always the best choice for all applications. **Table 1** summarizes typical noise parameters for the three common amplifier designs.

Table 1. Typical Noise Specifications for Amplifier Designs

INPUT STAGE	VOLTAGE NOISE	CURRENT NOISE	INPUT BIAS CURRENT	OVERALL PERFORMANCE
Bipolar[1]	1.8nV/$\sqrt{Hz}$	1.2pA/$\sqrt{Hz}$	80nA	Good
JFET	>10nV/$\sqrt{Hz}$	0.5fA/$\sqrt{Hz}$	>1pA	Better
CMOS[2]	4.5nV/$\sqrt{Hz}$	0.5fA/$\sqrt{Hz}$	1pA	Best

1. Data from the MAX410.
2. Data from the MAX4475.

Considering all sources of noise, the latest amplifiers with a CMOS-input stage, such as the MAX4475, offer the best compromise of noise performance for lower frequency analog applications and for almost any front-end application, especially high-source-impedance, wide bandwidth circuits.

A similar version of this article appeared in the August 2004 edition of *Electronic Products*.

Application Note 3642: http://www.maxim-ic.com/an3642

More Information
For technical questions and support: http://www.maxim-ic.com/support
For samples: http://www.maxim-ic.com/samples
Other questions and comments: http://www.maxim-ic.com/contact

AN3642, AN 3642, APP3642, Appnote3642, Appnote 3642