Build An Ultra-Low-Noise Voltage Reference

• **WALT JUNG** • *Analog Devices Inc., Technology Way, Norwood, MA 02062-1988; (617) 329-4700.*

As any analog designer knows, voltage-reference noise can be a major contributor to system noise if not given the proper attention. However, designers can build a fairly simple ultra-low-noise voltage reference to avoid such problems. A first step toward lowering system noise is to use a buried-Zener reference rather than a bandgap unit when possible. This helps minimize noise because buried-Zener references have noise outputs on the order of 100 nV/√Hz at 10 V. Comparing noise as a percentage of the voltage scale, the best bandgaps have four times the noise of buried-Zener references.

Unfortunately, even a noise density of 100 nV/√Hz may be insufficient when operating with high-resolution data converters. This is especially true with converters of 16 or more bits and full scale ranges of 5 V or less. For example, 100 nV/√Hz of noise in a 20-kHz, –3-dB bandwidth results in 17.7 μV rms (≈ 100 μV pk-pk) while one LSB in a 5-V scaled system is about 76 μV. High-performance systems, then, can easily require low-noise references.

Consider a low-noise reference circuit that's optimized for both ac and dc operation and produces an ultra-low-noise buffered reference output voltage *(Fig. 1)*. Output noise density is lower than 1.5 nV/√Hz over a voltage reference range of +5 V to +10 V with 20 mA or more load current available. U1, which is either a 5- or 10-V 3-terminal buried-Zener or bandgap reference IC, establishes the circuit's basic reference voltage. In this circuit, the AD587 device that's used is a 10-V buried-Zener reference, which is preferable for lowest noise. The AD587, which operates from supplies of +13.5 V to 36 V, has low noise of 100 nV/√Hz.

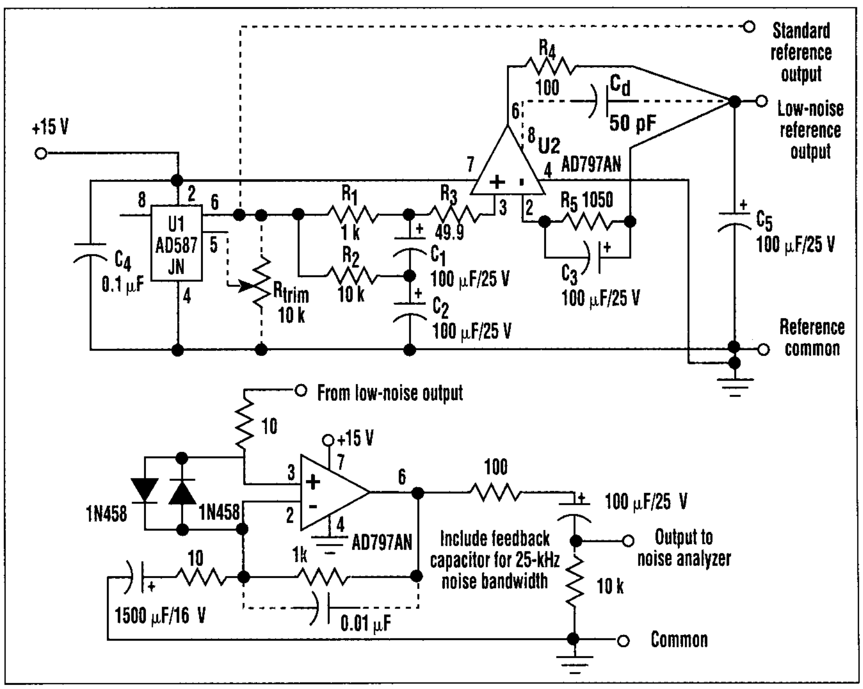
A stable 10-V ±10 mV output from U1 is applied to a noise filter consisting of R_1, C_1, and C_2. This filter is unusual because it uses electrolytic capacitors to achieve a low corner frequency, a design step that usually suffers dc leakage errors. In this case, however, a dc bootstrap is used. The lower capacitor C_2 is allowed to leak, producing a slight dc drop across R_2. The upper capacitor C_1 then sees only the small R_2 drop as an effective bias potential, which is orders of magnitude smaller than the applied 10 V. As a result, there is negligible dc drop across R_1 due to capacitor leakage, and the configuration has low dc error as a filter. For the values shown, the –3-dB point is about 1.7 Hz, and the filter reduces noise at 100 Hz by nearly 40 dB.

The ultra-low-noise unity-gain buffer uses an AD797 op amp to buffer the filter's low-noise, dc-accurate output. In the U2 stage, all resistances are minimum in value to preserve the lowest noise possible. Feedback sense resistor R_5 serves as bias compensation for $R_1 + R_3$, and is ac-bypassed to eliminate Johnson noise. Resistor R_3's function may not be obvious—it limits potential surge currents in the U2 input stage and also preserves stability.

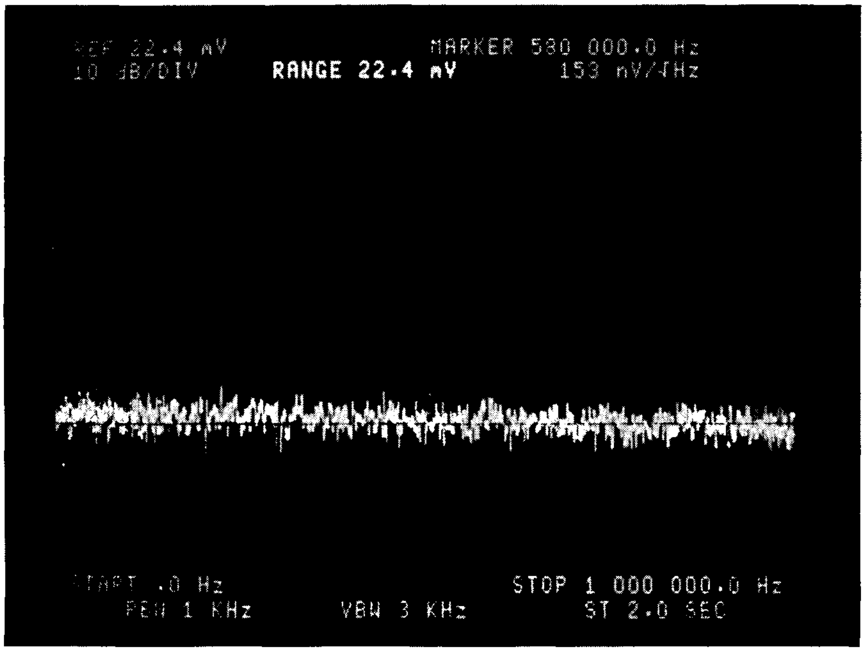
With this detailed attention paid to noise levels, the theoretical minimum noise from U2 with a noiseless source would approach 1.27 nV/√Hz (the RSS addition of the AD797 e_n at 0.9 nV/√Hz and a 50-Ω resistor at 0.9 nV/√Hz, neglecting bias current noise). This level of noise is so low that special techniques are required to measure it with any confidence. The noise floor of standard lab analyzers is about an order of magnitude higher, so the x100 gain preamp circuit shown in the inset was used to measure noise. Using an AD797 op amp, this circuit should have a theoretical minimum noise of about 1 nV/√Hz with a bandwidth between 10 and 1,000,000 Hz. An optional 0.01-μF feedback capacitor can tailor this stage to a 16-kHz bandwidth (without this capacitor the AD797 gain-bandwidth results in a 1-MHz bandwidth).

AC PERFORMANCE

Measured through the x100 wideband preamplifier, this reference's output noise level was observed to be



1 **A reference circuit that's optimized for both ac and dc operation produces an ultra-low-noise buffered output voltage of 5-10 V. The circuit's basic reference voltage is established by U1, a buried-zener or bandgap reference IC. U1's stable 10-V ±10 mV output is applied to a noise filter consisting of R_1, C_1, and C_2.**



2 **The noise output of the preamp is measured at 153 nV/√Hz, which is equal to approximately 1.5 nV/√Hz at the reference output.**

about 150 nV/√Hz, and was also relatively flat over the frequency spectrum up to 1 MHz *(Fig. 2)*. While other low-noise amplifiers can provide sub-1-nV/√Hz voltage noise below 100 kHz, the AD797 op amp has the advantage of this essentially flat noise spectrum to 1 MHz. The measurement's equivalent input-referred noise is 1/100 of the observed level, or 1.5 nV/√Hz, and composed of both reference noise and measuring-pre-amp noise. Because the reference noise and the instrumentation noise is of the same order, it's difficult to say exactly what the reference output noise is. It's on the order of 1.25 nV/√Hz, and will vary slightly with frequency.

The ac output impedance was about 50 mΩ at 50 kHz with the circuit operating U2 as a conventional op amp (this data is not shown). However, the AD797 op amp has an output stage that can actually reduce the effective output impedance over broad bandwidths using a unique architecture.[1] This optional feature is employed by connecting C_d, a 50-pF capacitor, around R_1 *(Fig. 1, again)*. When this is done, the output impedance can be lowered even further. In this circuit, it yielded a 15- to 20-dB improvement.

DC PERFORMANCE

This circuit's dc performance is also exceptional. The AD797 op amp has a typical current limit of 50 mA and can provide output currents of 20 mA or more—at least twice that of a typical IC reference. The buffer's dc errors are minimal because of the AD797's low offset voltage (80 μV max) and offset current (400 nA max) that produce an equivalent offset of 500 μV. If low leakage (I_l=0.001 CV), well derated (25-V) capacitors are used for C_1 and C_2, then the effective leakage of C_1 can be lower than U2's bias current.

The dominant dc reference errors under these conditions will be the calibration error of the U1 device, which is ±10 mV for the AD587JN. This can be optionally trimmed via resistor R_{trim}, or a tighter grade part like the AD587KN can be employed. Reference devices with drift of even 1 ppm/°C are unlikely to be compromised with this circuit because for a 10-V output, the 1-μV/°C drift of the AD797 op amp is equivalent to only 0.1 ppm/°C.

In principle, this basic idea of filtering can be used with any reference device, including standard 10-V/5-V bandgap devices such as the REF-01 and REF-02. If the U2 buffer op amp is substituted, noise will be limited to the voltage-noise characteristic of the device used. With standard devices for U2, such as the OP-07 or OP-27 op amps, the resulting output-noise levels would be on the order of 10 nV/√Hz or 3 nV/√Hz, respectively. ED

Walt Jung
Analog Devices

Office: (410) 692-6702 / FAX: (410) 557-6581

Date: Thu 07-08-1993 09:10:58

To: Readers of Electronic Design 6/24/93 Analog Issue

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Dear ED Reader:

The above special issue of Electronic Design contains useful articles on analog circuit design. As an author in this issue, the following errata notice is provided for the convenience of readers:

A) "Analog Signal Processing Concepts Get More Efficient" (P12)

1) In Fig. 1, the value of the last (rightmost) resistor in the R/2R ladder should be "R", not "2R".

2) In Fig. 2, U2 (14 pins, right/top) is an AD636.

3) In Fig. 6, U1 (8 pins, top) is a REF-195.

4) In Fig. 6, C1 should be 1μF, not 0.1μF.

B) "Build An Ultra Low-Noise Voltage Reference" (P74)

1) Reference #1 was cited in the text, but inadvertently dropped from the article. It is:
   1. Goodenough, F.; AD797 discussions in: "Trio of Op Amps Handle Milliwatts to Kilowatts", Electronic Design, June 11, 1992.

2) In Fig. 1, C5 should be 10μF/25V (Note: The 100μF/25V shown may also work, but the lower value was used in the lab tests).

Thanks for your interest. If there should be any questions on either of the above two articles, I can be reached at the numbers above.

Walt Jung