Pocket-Size White Noise Generator for Quickly Testing Circuit Signal Response

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Noise in electrical circuits is typically the enemy. Any self-respecting circuit should output as little noise as possible. Nevertheless, there are cases where a well-characterized source of noise with no other signal is entirely the desired output.

Circuit characterization is such a case. The outputs of many circuits can be characterized by sweeping the input signal across a range of frequencies and observing the response of the design. Input sweeps can be composed of discrete input frequencies or a "swept sine." Extremely low frequency sine waves (below 10Hz) are difficult to produce cleanly. A processor, DAC, and some complex, precise filtering can produce relatively clean sine waves; but, for each frequency step, the system must settle, making slow work of sequential full sweeps featuring many frequencies. Testing fewer discrete frequencies can be faster, but increases the risk of skipping over critical frequencies where high Q phenomena reside.

A white noise generator is simpler and faster than a swept sine wave because it effectively produces all frequencies at the same time with the same amplitude. Imposing white noise at the input of a device under test (DUT) can quickly produce an overview of the frequency response over an entire frequency range. In this case, there is no need for expensive or complex swept sine wave generators. Rather, simply connect the DUT output to a spectrum analyzer and watch. Using more averaging and longer acquisition times produces a more accurate output response across the frequency range of interest.
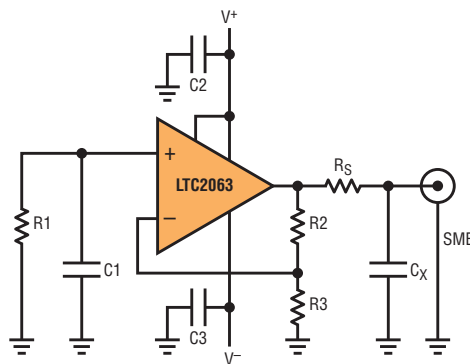

Figure 1. Full schematic of white noise generator. Low drift micropower LTC2063 amplifies the Johnson noise of R1.

The expected response of the DUT to white noise is frequency-shaped noise. Using white noise in this fashion can quickly expose unexpected behavior such as weird frequency spurs, strange harmonics and undesirable frequency response artifacts.

Table 1. Noise voltage density of various resistors

RESISTOR	NOISE VOLTAGE DENSITY
10Ω	0.402nV/$\sqrt{\text{Hz}}$
100Ω	1.27nV/$\sqrt{\text{Hz}}$
1k	4.02nV/$\sqrt{\text{Hz}}$
10k	12.7nV/$\sqrt{\text{Hz}}$
100k	40.2nV/$\sqrt{\text{Hz}}$
1M	127nV/$\sqrt{\text{Hz}}$
10M	402nV/$\sqrt{\text{Hz}}$

Furthermore, a white noise generator allows a careful engineer to test a tester. Lab equipment that measures frequency response should produce a flat noise profile when measuring a known flat white noise generator.

On the practical side, a white noise generator is easy to use, small enough for compact lab setups, portable for field measurements, and inexpensive. Quality signal generators with myriad settings are attractively versatile; however, versatility can hamper quick frequency response measurements. A well-designed white noise generator requires no controls, yet produces a fully predictable output.

NOISY DISCUSSION

Resistor thermal noise, sometimes called Johnson noise or Nyquist noise, arises from thermal agitation of charge carriers inside a resistor. This noise is approximately white, with nearly Gaussian distribution. In electrical terms, the noise voltage density is given by

$$V_{NOISE} = \sqrt{(4k_B TR)}$$

where k_B is the Boltzmann's constant, T the temperature in degrees Kelvin, and R the resistance. Noise voltage arises from the random movement of charges flowing through the basic resistance, a sort of $R \bullet I_{NOISE}$. Table 1 shows examples at 20°C.

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A 10M resistor, then, represents a 402nV/√Hz wideband voltage noise source in series with the nominal resistance. A gained up resistor-derived noise source is fairly stable as a lab test noise source, as R and T variations affect noise only by square root. For instance, a change of 6°C from 20°C is a change of 293K to 299K. Because noise density goes as the square root of temperature, a change of 6°C temperature leads to a relatively small 1% noise density change. Similarly with resistance: a 2% resistance change leads to a 1% noise density change.

Consider Figure 1. A 10M resistor R1 generates white, Gaussian noise at the positive terminal of an op amp. Resistors R2 and R3 gain the noise voltage to the output. Capacitor C1 filters out chopper amplifier charge glitches. Output is a 10μV/√Hz white noise signal.

- Gain (1 + R2/R3) is high, 21V/V in this example.
- Even if R2 is high (1M), the noise from R2 compared to the gained up R1 noise is inconsequential.
- An amplifier for the circuit must have sufficiently low input-referred voltage noise so as to let R1 dominate as the noise source. The reason: the resistor noise should dominate the overall accuracy of the circuit, not the amplifier.
- An amplifier for the circuit must have sufficiently low input-referred current noise to avoid (I_N • R2) to approach (R1 noise • Gain) for the same reason.

HOW MUCH AMPLIFIER VOLTAGE NOISE IS ACCEPTABLE IN THE WHITE NOISE GENERATOR?

Table 2 shows the increase in noise from adding independent sources. A change from 402nV/√Hz to 502nV/√Hz is only 1.9dB in log volts, or 0.96 power dB. With op amp noise ~50% of the resistor noise, a 5% uncertainty in op amp V_{NOISE} changes the output noise density by only 1%.

A white noise generator could employ only an op amp, without a noise-generating resistor. Such an op amp must exhibit a flat noise profile at its input. However, often the noise voltage is not accurately defined, and has a large spread over production, voltage and temperature.

Other white noise circuits may operate based on a Zener diode with far less predictable characteristics. Finding an optimal Zener diode for stable noise with μA of current can be difficult however, particularly at low voltage (< 5V).

Some high end white noise generators are based on a long pseudorandom binary sequence (PRBS) and special filters. Using
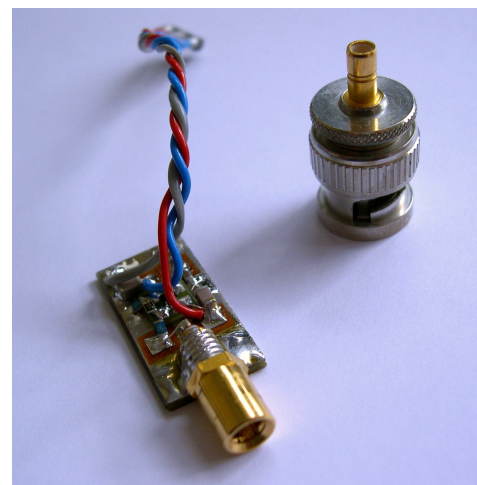

Figure 2. Prototype pocket-size white noise generator

a small controller + DAC may be adequate; however, making sure that the DAC does not produce settling glitches, harmonics or intermodulation products is something for experienced engineers. Additionally, choosing the most appropriate PRBS sequence adds complexity and uncertainty.

Table 2. Contribution of op amp noise

R_{NOISE}(nV/√Hz)	AMP e_n	TOTAL INPUT REFERRED
402nV/√Hz	300	501.6nV/√Hz
402nV/√Hz	250	473.4nV/√Hz
402nV/√Hz	200	449.0nV/√Hz
402nV/√Hz	150	429.1nV/√Hz
402nV/√Hz	100	414.3nV/√Hz

With approximately 300Hz–400Hz of flat bandwidth, the LTC2063 resistor-noise-based circuit could be useful to test some instruments for 50Hz/60Hz mains frequency, perhaps geophone applications. The range is suitable for testing various "VLF" applications (e.g., sensor systems), as the frequency range extends down to << 0.1Hz.

LOW POWER ZERO-DRIFT SOLUTION

Two project design goals dominate this project:

- An easy-to-use white noise generator must be portable, i.e., battery powered, which means micropower electronics.

- The generator must provide uniform noise output even at low frequencies, below 0.1Hz and beyond.

Considering the preceding noise discussion and these critical constraints, the LTC2063 low power zero drift op amp fits the bill.

The noise voltage of a 10M resistor is $402nV/\sqrt{HZ}$; LTC2063's is roughly half. The noise current of a 10M resistor is $40fA/\sqrt{HZ}$; the LTC2063's is less than half. The LTC2063 fits neatly into a battery application inasmuch as its supply current 1.4µA typical, and total supply can go down to 1.7V (rated at 1.8V). Since low frequency measurements by definition require long settling times, this generator must remain powered by a battery for extended periods of time.

Noise density of the LTC2063 input is roughly $200nV/\sqrt{HZ}$, and noise is predictable and flat over the frequency range (within ±0.5dB). Assuming that the LTC2063's noise is 50% of thermal noise and op amp voltage noise changes 5%, output noise density changes only 1%.

Zero-drift op amps do not have zero 1/f noise by design. Some are better than others, and, especially for current noise, it is more common that the wideband spec is wrong or that 1/f noise is much higher than suggested in
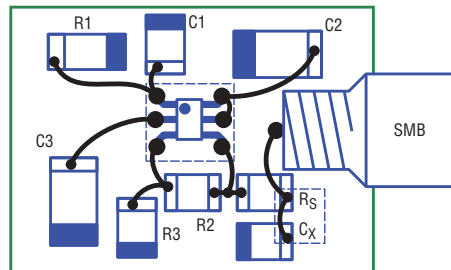
NOTE: BLUE FILL SMD TERMINALS ARE GROUNDED
R1 = 10MΩ MMA0204 (MINIMELF)
  VISHAY/BEYSCHLAG 1% TC50 (= THIN FILM)
R2 = 1M, R3 = 49k9; R_S = 10k; all 1% TC100 THICK FILM
C1 = 22pF C0G 5%; C2/C3 = 0.1µF C0G
C_X = 47nF C0G 5% (SEE TEXT: "OPTIONAL TUNING")

Figure 3. Gizmo layout

the data sheet. For some zero-drift op amps, the data sheet noise plot does not go down to the mHz frequency region, possibly masking 1/f noise.

A chopper stabilized op amp could be a solution to keep the noise "flat" at very low frequency. That said, the high frequency noise bump and switching noise must not spoil the performance. The data shown here supports the use of LTC2063 in the face of these challenges.

CIRCUIT DESCRIPTION

The thin film R1 (Vishay/Beyschlag MMA0204 10MΩ) generates most of the noise. The MMA0204 is one of few 10M options to combine high quality with low cost. In principle, R1 could be any 10M, as signal current is very small, so 1/f noise can be neglected. It is best to avoid low cost thick film chips of questionable accuracy or stability for the primary element of this generator.

For best accuracy and long term stability, R2, R3, R_S could be 0.1% thin film,

e.g., TE CPF0603. C2/C3 could be one of most dielectrics; C0G can be used to guarantee low leakage current.

IMPLEMENTATION DETAILS

Loop area R1/C1/R3 should be minimized for best EMI rejection. Additionally, R1/C1 should be very well shielded from electrical fields; see "EMI Considerations" below. Although not critical, as noted above, R1 should be shielded from large temperature changes. With good EMI shielding, thermal shielding is often adequate.

The LTC2063 rail-to-rail input voltage transition region of the V_{CM} range should be avoided, as crossover may result in higher, less stable noise. For best results, use at least 1.1V for V+ with the input at 0 common mode.

Note that R_S of 10k may seem high, but the micropower LTC2063 presents a high output impedance; even 10k does not fully decouple the LTC2063 from load capacitance at its output. For this white noise generator circuit, some output capacitance that leads to peaking can be a design feature rather than a hazard.

The output sees 10k R_S and a 50nF C_X to ground. This capacitor C_X will interact with the LTC2063 circuit, resulting in some peaking in the frequency response. This peaking can be used to extend the flat bandwidth of the generator, in much the same way that port holes in loudspeakers attempt to expand the low end. A high-Z load is assumed (> 100k), as a lower-Z load would significantly reduce output level and may also affect peaking.

Zero-drift op amps do not have zero 1/f noise by design. Some are better than others, and, especially for current noise, it is more common that the wideband spec is wrong or that 1/f noise is much higher than suggested in the data sheet. For some zero-drift op amps, the data sheet noise plot does not go down to the mHz frequency region, possibly masking 1/f noise.
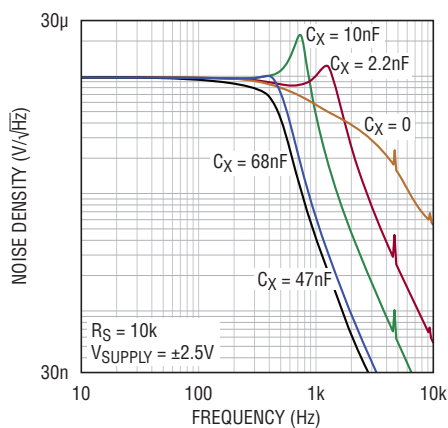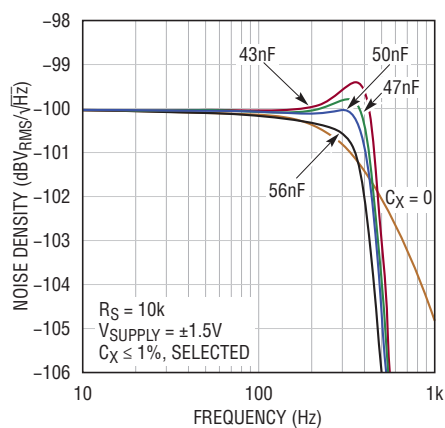

Figure 4. Output noise density of design in Figure 1

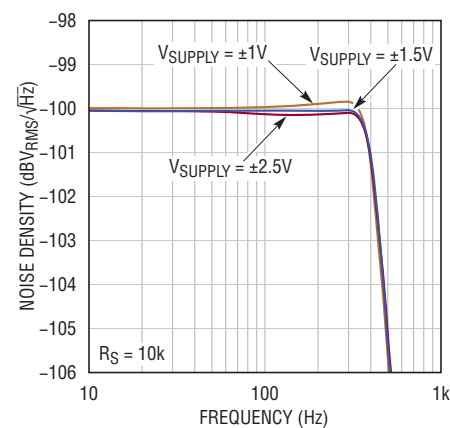Figure 5. Zoomed in view of output noise density of design in Figure 1

Figure 6. Output noise density for various supply voltages

OPTIONAL TUNING

Several IC parameters (e.g., R_{OUT}, GBW) affect flatness at the high frequency limit. Without access to a signal analyzer, the recommended value for C_X is 47nF, which typically yields 200Hz–300Hz (−1dB) bandwidth.

Nevertheless, C_X can be optimized for either flatness or bandwidth, with C_X = 30nF–50nF typical. For wider bandwidth and more peaking, use a smaller C_X. For a more damped response, use a larger C_X.

Critical IC parameters are related to op amp supply current: parts with low supply current may require a somewhat larger C_X, while parts with high supply current most likely require less than 30nF while achieving wider flat bandwidth.

Plots shown here highlight how C_X values affect closed loop frequency response.

MEASUREMENTS

Output noise density vs C_X (at R_S = 10k, ±2.5V supply) is reported in Figure 4. The output RC filter is effective in eliminating clock noise. The plot shows output vs frequency for C_X = 0 and C_X = 2.2nF/10nF/47nF/68nF.

C_X = 2.2nF exhibits mild peaking, while peaking is strongest for C_X = 10nF, gradually decreasing for larger C_X. The trace for C_X = 68nF shows no peaking, but has visibly lower flat bandwidth. A best result is for C_X ~ 47nF; clock noise is three orders of magnitude below signal level. Due to limited vertical resolution, however, it is impossible to judge with fine precision the flatness of output amplitude vs frequency. This plot was produced using ±2.5V battery supply, though the design allows use of two coin cells (about ±1.5V).

Figure 5 shows flatness "magnified" on the Y-axis. For many applications, flatness within 1dB is enough to be

useful, and < 0.5dB is exemplary. Here, C_X = 50nF is best (R_S = 10k, V_{SUPPLY} ±1.5V); C_X = 45nF … 55nF is acceptable.

High resolution flatness measurements take time: for this plot (10Hz–1kHz, 1000 averages) about 20 minutes per trace. The standard solution uses C_X = 50nF. The traces shown for 43nF, 47nF and 56nF, all Cs < 0.1% tolerance, show a small but visible deviation from best flatness. The orange trace for C_X = 0 was added to show that peaking increases flat bandwidth (for Δ = 0.5dB, from 230Hz to 380Hz).

2× 0.1µF COG in series is probably the simplest solution for an accurate 50nF. 0.1µF COG 5% 1206 is easy to procure from Murata, TDK, Kemet. Another option is a 47nF COG (1206 or 0805); this part is smaller, but may not be as commonly available. As stated above, optimum C_X varies with actual IC parameters.

Flatness was also checked vs supply voltage; see Figure 6. The standard circuit

The white noise generator shown here is a small but essential tool. With long measurement times the norm for LF applications, a simple, reliable, pocketable device that can produce near instantaneous circuit characterization is a welcome addition to the engineer's toolbox. Unlike complex instruments with numerous settings, this generator requires no user manual.

is ±1.5V. Changing supply voltage to ±1.0V or ±2.5V shows a small change in peaking as well as a small change in the "flat" level (due to V_N changing vs supply, with thermal noise dominant). Both peaking and "flat" level change ~0.2dB over the full range of supply voltage. The plot suggests good amplitude stability and flatness when the circuit is powered from two small batteries.

For this prototype at ±1.5V supply, flatness was within 0.5dB up to approximately 380Hz. At ±1.0V supply, flat level and peaking slightly increase. For ±1.5V to ±2.5V supply voltage, output level does not visibly change. Total V_{P-P} (or V_{RMS}) output level depends on the "fixed" $10\mu V/\sqrt{Hz}$ density, as well as on bandwidth. For this prototype, output signal is ~1.5mV_{P-P}. At some very low frequency (mHz range), noise density may increase beyond the specified $10\mu V/\sqrt{Hz}$. For this prototype it was verified that at 0.1Hz, noise density is still "flat" at $10\mu V/\sqrt{Hz}$.

Stability vs temperature: thermal noise dominates, so for T = 22(±6)°C, amplitude change is ±1%, a change that would barely be visible on a plot.

EMI CONSIDERATIONS

The prototype uses a small copper foil with Kapton insulation as a shield. This foil, or "flap," is wrapped around the input components (10M + 22pF), and soldered to ground on the PCB backside. Changing the position of the flap has significant effect on sensitivity to EMI and risk of low frequency (LF) spurs. Experimentation suggests that LF spurs that occasionally

show are due to EMI, and that spurs can be prevented with very good shielding. With the flap, the prototype gives a clean response in the lab, without any additional mu-metal shielding. No mains noise or other spurs appear on a spectrum analyzer. If excess noise is visible on the signal, additional EM-shielding might be needed.

When an external power supply is used instead of batteries, common mode current can easily add to the signal. It is recommended to connect the instrument grounds with a solid wire and use a CM-choke in the supply wires to the generator.

LIMITATIONS

There are always applications that require more bandwidth, like full audio range or ultrasound range. More bandwidth is not realistic on a few µA of supply current. With approximately 300Hz–400Hz of flat bandwidth, the LTC2063 resistor-noise-based circuit could be useful to test some instruments for 50Hz/60Hz mains frequency, perhaps geophone applications. The range is suitable for testing various "VLF" applications (e.g., sensor systems), as the frequency range extends down to << 0.1Hz.

The output signal level is low (< 2mV_{P-P}). A follow-on LTC2063 configured as a non-inverting amp with a gain of five and further RC output filter can provide a similarly well controlled flat wideband noise output to 300Hz, with larger amplitude.

In the case that does not maximize the closed loop frequency range, a capacitor across the feedback resistor

can lower the overall bandwidth. In this case the effects of R_S and C_X will have less, or even negligible effect at the edge of the closed loop response.

CONCLUSION

The white noise generator described here is a small but essential tool. With long measurement times the norm for LF applications, a simple, reliable, pocketable device that can produce near instantaneous circuit characterization is a welcome addition to the engineer's toolbox. Unlike complex instruments with numerous settings, this generator requires no user manual. This particular design features low supply current, essential for battery-powered operation in long duration VLF application measurements. When supply current is very low, there is no need for on/off switches. A generator that works on batteries also prevents common mode currents.

The LTC2063 low power zero-drift op amp used in this design is the key to meeting the constraints of the project. Its features enable use of a noise generating resistor gained up by a simple noninverting op amp circuit. ∎