BUILD THE JCAN TO MEASURE RESISTOR NOISE

You have probably heard someone say that some resistors are "noisier" than others. All resistors generate electrical signals.

Without power applied, most like-valued resistors generate about the same amount of noise at a given temperature.

This noise is mostly thermal or "Johnson" noise[1]. When power is applied, typically as a current flowing through the resistive material of a resistor, there can also be "shot" noise and other sources of noise including "1/f" noise, so named for its distribution over frequency. This 1/f noise can be attributed to internal resistor composition and connections between the resistive material (film, carbon composition, or resistive wire) and the resistor leads[2].

You may have literally heard the difference between resistor compositions while testing an audio pre-amplifier with different types of components. Or, if you work with high gain amplifiers used to measure signals, you might also be interested in resistor noise. It is usually of concern in small signal transistor or tube applications, as well as in op-amp circuits generally using two or more resistors. I recently started wondering how to measure the noise from a resistor. I wanted to measure it — in some common unit — just like an ohmmeter measures resistance.

I started my quest by placing various resistors on the input of my best meters that can measure small AC voltages. It didn't work. Next, I looked up resistor noise in several of my electronics books, including a few of the classic electronics texts. They all said, "It's easy, just use an amplifier." It still didn't work.

After several weeks of studying JFET and op-amp data sheets and several different circuit techniques, it turns out that it really is pretty easy, once you know the three problems that need to be solved and understand why they matter. Whether you are an audiophile, an instrument designer, an EE, physics student, or an electronics enthusiast, you might find these problems in measuring resistor noise interesting. You might even want to build a "JCan" (the "J" is for Johnson) and try it out yourself!

The JCan is a very sensitive instrument that can measure resistor noise when used with a standard AC voltmeter capable of measurements in the range of 1-20 mVAC at audio frequencies. The JCan can also measure thermal noise plus shot noise by injecting a small current into resistors under test. All that is needed to calibrate the JCan is a small selection of resistors of known values. Once the calibration numbers have been determined using a relatively simple spreadsheet to analyze your raw data, the JCan can be used to compare different types of resistors. For example, under power, the difference between the noise generated by metal film resistors and carbon composition resistors is easy to measure.

Before considering the direct measurement of Johnson (thermal) noise, let's look at how small of a signal we are looking for. Johnson noise is defined by the following equation:

$$Vnoise = \sqrt{4 \times k \times T \times R \times BW}$$

or

$$Vnoise^2 = 4 \times k \times T \times R \times BW$$

where: k is Boltzmann's constant (~1.381 × 10^{-23}), T is the ambient temperature in Kelvin, R is the resistance of the resistor under test in ohms, and BW is the bandwidth in Hertz being considered (the pass band of the preamp and meter combined). Most manufacturers specify thermal noise in "1 Hz bandwidth," which we can find by dividing Vnoise by $\sqrt{BW}$. The $nV/\sqrt{Hz}$ thermal noise for resistors at room temperature ranges from about 4 nV (nanovolts or 1 x 10^{-9}V) for a 1K resistor to about 58 nV for a 200K resistor. Over a bandwidth of about 20 kHz, the corresponding expected noise voltages range from about 0.6 μV for a 1K resistor to about 8 μV for a 200K resistor.

There are three crucial parameters that must be considered to successfully measure resistor thermal noise: (1) input sensitivity; (2) input capacitance; and (3) input noise.

WHY IS $nV/\sqrt{Hz}$ THE UNIT OF NOISE (AND WHY IS $\sqrt{Hz}$ IN THE DENOMINATOR?)

There are many references in this article to an equivalent noise value for a 1 Hz bandwidth. The units for these "normalized" numbers are nV / root Hz or $nV/\sqrt{Hz}$. To see why $\sqrt{Hz}$ ends up in the denominator, consider that a 1 μV noise signal measured over a 20 kHz bandwidth is equivalent to $1uV/\sqrt{20,000Hz}$ or $1uV/141.4\sqrt{Hz}$. Dividing 1 μV by 141.4 gives $7.1nV*1/\sqrt{Hz}$ or $7.1nV/\sqrt{Hz}$. In this context, the term normalized simply means that a noise value has been divided by the square root of the bandwidth so that it can easily be compared to another value or set of values without regard to the bandwidth used to make the actual measurement.

Problem No. 1:

Most modern DMMs cannot directly measure μV AC voltages.

Notice that over a wider bandwidth of 300 kHz, resistor thermal noise voltages become larger, ranging from about 2 μV for a 1K resistor to about 32 μV for a 200K resistor. It would seem that with a very sensitive bench multimeter you should be able to directly measure resistor thermal noise.

For example, the HP/Agilent 34401A, 6-1/2 digit multimeter, has a 100 mV AC voltage scale with about a 300 kHz bandwidth. The scale is defined as 100.0000 mV; however, when a 6K resistor is connected to the input and the meter is set to AC volts, the DMM indicates 000.000 mV.

The reason is that this otherwise excellent DMM was not designed to measure AC voltage below about 1 mV. The HP/Agilent 34401A, however, is an ideal DMM to use with the JCan. (If you do use a 34401A, set the AC filter to "slow 3 Hz" — the meter response time, not the input bandwidth — and four digits.)

Problem No. 2:

Some classic AC millivoltmeters can measure down to 10 μV, but still cannot directly measure resistor noise because of their relatively high input capacitance.

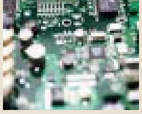
Next, we turn to a classic AC millivoltmeter such as the HP 400 GL. The 400 GL has a 0.1 mV scale (100 μV) that reads down to 10 μV. The bandwidth is 100 kHz with the internal filter switched on. This means that the 400 GL should be able to read a $\sqrt{Hz}$ signal of 10 μV/$\sqrt{100kHz}$ or to about 32 $nV/\sqrt{Hz}$; 41$nV/\sqrt{Hz}$ is roughly equivalent to a 100K resistor. A 1/4 watt 100K resistor with short leads was tied under the input five-way binding posts of the 400 GL. A metal shield was then placed over the posts and connected to the common terminal (aluminum foil is okay, too).

For a 100 kHz bandwidth, the 400 GL expected reading is about 13 μV. Although there seems to be some indication, the actual reading is below 10 μV. The problem is that most analog AC millivoltmeters have an input capacitance on the order of 15 to 30 pf (picofarads). While that sounds small, when combined with 100K, it forms an input RC filter, limiting the bandwidth to about 57 kHz for an input capacitance of 28 pF; 57 kHz is far lower than the bandwidth of the HP 400 GL's 100 kHz filter bandwidth, which explains the low reading of about 9.8 μV, just below the 10 μV low end scale marking.

For higher value Rs, the bandwidth is further limited and the noise voltage becomes lower. Ironically, once input capacitance dominates, the thermal noise measurement becomes nearly independent of resistance. To directly measure noise voltage over a reasonable range of resistance values — such as 1K to 200K — very low input capacitance is essential. For bandwidth calculations, also note that the HP 400 GL bandwidth (with the 100 kHz filter turned off) is

■ JCan — top view.

■ JCan with HP 400E.



THE HP 400 SERIES METERS

The HP 400 series AC voltmeters are very useful and widely available as surplus instruments. Any of them are ideal companion instruments for working with the JCan. The 400 F, 400 FL, and 400 GL have the most sensitive ranges of 0.1 mV (100 µV) full scale. The "L" indicates the presence or emphasis of the log scale on the display. These meters also have amplified AC voltage output terminals and can be used as preamps for a digital scope, less sensitive AC voltmeter, or a chart recorder with an AC voltage range. They also have front panel switch selectable 100 kHz filters. (The minimum JCan output is about 1 mV, so a 100 µV scale is not needed for the JCan project.)

The 400 E and 400 EL have BNC input connectors and optional outputs, but not the 100 kHz filters (also not needed for the JCan work). Among the optional outputs on some of the 400 E / EL meters is a DC output representative of the AC levels that could be useful when used with a chart recorder to look at signals — such as resistor noise — over relatively long time periods. The 403B is a smaller package (shorter depth) and has no AC output. The 403B also can have batteries that almost certainly will need to be changed and may have leaked. Note that the HP 400 series is all "average responding" AC voltmeters. Average responding means that a meter is calibrated for AC sine wave waveforms in volts RMS (root mean squared). For noise measurements, the reading will be low by a factor of 1.13, thus HP 400 noise values will read low and should be multiplied by a correction factor of 1.13^2. "True RMS" meters, such as the Agilent 34401A, do not need this correction factor and can be read directly. With the permission of Agilent, we will be posting HP catalog pages and manuals for free downloading related to the 400 series AC voltmeters on our website at **www.gellerlabs.com** under "manuals."

far higher than the specified 4 MHz bandwidth, often exceeding 10 MHz (albeit only "calibrated" to 4 MHz).

Problem No. 3:
Low input noise is important.

As I began to investigate preamplifier circuits, it quickly became apparent that just as input capacitance limits the high end of resistance values that can be measured, the amplifier's own input noise limits the low end. The thermal noise expected from a 1K resistor is about $4nV/\sqrt{Hz}$, therefore input noise must be lower than $4nV/\sqrt{Hz}$ to measure the thermal noise from a 1K resistor.

JFETs are among the most suitable transistors for use in a low capacitance, low input noise audio range preamp. The problem is that most existing designs — such as microphone amplifiers — are not suitable for use over a wide range of input resistances. Also, many of the classic low noise JFETs have a relatively high input capacitance rendering them less useful for the JCan preamp application. Some of our first JCan prototypes achieved low input capacitance at the expense of relatively high input noise. These prototypes could only measure thermal noise down to about 10K.

Building the Circuit

A BF244A JFET transistor (for ultra low input capacitance) combined with a low noise LT1028 op-amp from Linear Technology was found to solve all three problems. A third op-amp stage further helps to shape the bandwidth and to provide enough gain so that most modern bench DMMs can be used with the JCan to directly measure resistor thermal noise. While in some analog designs there can be an advantage to using a linear power supply to limit power supply noise, here, batteries are a must. Two 9V batteries power the JFET, op-amps, and provide the current to observe shot noise plus thermal noise when comparing resistors.

Since we are measuring very tiny voltages, it is essential that the preamp be well shielded. A paint can provides the needed shielding[4]. A half gallon can from the Cary Company of Addison, IL that has the same diameter as a one gallon paint can lid (but a height of only 4") works well for this experiment. I found that the "half can" is more convenient to work with on the lab bench. Standard safety rules apply when drilling holes in the lid. *Always use safety glasses!* I found that a high drill speed works best when cutting small holes in the tin lid. A step drill comes in handy for the 3/8" hole for the BNC connector. If you don't have a step drill, begin with a small hole and work up to the needed 3/8" final hole size. If your can has an epoxy interior coating, be sure to sand the epoxy off where the cover meets the can for good electrical contact.

The JCan preamp must be wired on a soldered proto board, printed circuit board (PCB), or perhaps dead bug wired (parts glued to a substrate with wires and components soldered between pins). The line-to-line capacitance on solderless breadboard is too high. (Geller Labs — **www.gellerlabs.com** — will offer a printed circuit board.) PCB graphics are also available for download from the *Nuts & Volts* website (**www.nutsvolts.com**) for do it yourself hobbyists to make their own PC cards.

We found that slit input posts to accept resistors under test can be made from connector jack inserts. For example, a gold solder socket intended for use in a D-sub connecter can work well. A solid #18 copper wire can be soldered to the jack and then soldered onto a PCB. Or, a PC hole can be sized to accept a jack directly soldered on the PCB. Make sure to align both slits so a resistor can be easily pushed into both test jacks.

The JCan circuit is relatively simple as to principle of operation. The input JFET allows a drain current of about 1 to 4 mA for the 10M; 0V DC bias gate resistor. C1 couples the thermal noise from a resistor under test into the first stage JFET amplifier. R2, the drain resistor, doubles as the input for the first stage LT1028 low noise amplifier. The net gain of both stages combined is on the order of 150 ± ~25. The BF244 drain current and net gain will vary among parts. Note that even with a battery supply, the power to the BF244 stage is further filtered to isolate it from the other stages.

The BF244 stage, as well as the resistor under test are referenced to both electronics common (0V between the two 9V batteries) and the can shield ground. Electrical safely tip: *In most cases, the tin can will not be directly tied to a house common (earth) ground, so be very careful that nothing on your bench connects a high voltage to the can!*

The first bandwidth shaping takes place in the combined BF244 and LT1028 stages. R2 and C2 form a first high pass filter (the low end frequency) and R1 and C10 form a first low pass filter (the high end frequency). At the output of the LT1028, R3 and C3 form another low pass filter. C15 and R6 form yet another high pass filter.

The last stage provides an additional gain of about 19.5 ± ~2 (R7/(R3+R6)). The purpose of the U2 stage is to create a large enough output signal that most bench DMMs can take over to measure the output AC voltage representing the thermal noise of the resistor under test. Another low pass filter is created by C14 and R7 and a final low pass output filter is created by R9 and C4. Some op-amps might not be able to directly drive the capacitance of a coax cable to a DMM, therefore R9 also helps to isolate the cable capacitance from the op-amp output.

The BF244A (Q1) offers both very low input gate capacitance, as well as extremely low device noise. The BF244A also has a nice bias point of drain current for zero Vgs (gate voltage). The BF244B or BF244C have very different drain currents at zero Vgs (Idss) and therefore are not suitable for use in the JCan. It is possible to use a 2N4416A JFET with a smaller drain resistor, higher drain current, and slightly degraded performance but the pin-out is different (gate at the end of the package) requiring a little bit of lead bending. Note also that some of the classic ultra low noise JFETs that are often used in high end audio preamps have a relatively high gate capacitance (6 to 25 pF) and are not suitable for use in this application. Also, there are few options for U1, the LT1028. It is crucial that U1 also have low voltage and current noise.

An AD797 also works for this stage. Also, the final U2 stage must have a sufficient gain-bandwidth product (GBW) for a relatively high closed loop gain (~ 20) and should be able to drive the capacitance of an output cable. The LT1357 is particularly well suited for this application. Note that if an op-amp with insufficient GBW is substituted for U2, the effective bandwidth of the JCan filter will be narrower than intended (about 20 kHz) with JCan filter performance modified by the op-amp rather than determined as intended by the filter RCs alone.

Testing

You can build and test the JCan one stage at a time, or build the entire circuit and then test in stages, or just power it up and see if the entire circuit works. Testing will largely depend on how much bench equipment you have available. First, place a shorting wire across the "resistor under test" jacks (but, not the upper current source jacks) to protect the JFET during initial testing.

The BF244 is not as ultra sensitive to handling as some of the older MOSFETs were, however, good static practice is still needed. This doesn't mean that you need a ground strap (unless you work in sneakers in carpeted rooms on dry days). The best static protection approach for using the JCan is simply to hold the can top first, then manipulate the next resistor under test into the test jacks while resting the edge of your hand on the can top. For best electrical safety, disconnect all other test leads while changing resistors under test.

Use the slide switch to remove the ±9V power when changing resistors under test. Also don't forget to turn off power at the end of testing, since the load current on the order of 10 mA is relatively high for a 9V cell (about 10 hours of total battery life is possible with only reasonable care, such as not leaving the JCan powered over night). JCan performance is not particularly dependent on battery voltage, so regulation and initial change in battery voltage during normal discharge is not of concern.

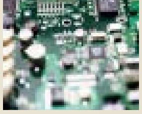
We use a relatively expensive C&K switch because it slides very easily and has high reliability contacts rated at 100,000 cycles. A more modest switch can suffice; just be sure it doesn't add noise by introducing intermittent contacts. Also, I found that removing the battery contacts to switch power is impractical since the snap contacts failed relatively quickly with repeated use.

If you have an ammeter handy, begin by connecting each battery one at a time and checking the load current. Up to about 17 mA is okay; much higher might indicate a short. It also might be good to first check from each battery snap terminal to common using an ohmmeter before connecting either battery to check for inadvertent short circuits.

Next, check the bias point of Q1 using a DC voltmeter. There should be about four to five volts across the drain and the source (V_{ds}). If not, replace R2 with a slightly higher or lower valued metal film resistor until this V_{ds} is achieved.

The following tests are optional; you may also proceed directly to Calibration and skip these tests. If you have a signal generator that can output 1 mV AC (either directly or with an attenuator such as a pad), you may want to test the combined BF244A/LT1028 stage. Unplug U2 for this test. Place a 50 ohm resistor in the resistor under test jacks — it presents a conveniently matched load for many types of signal generators. If your generator has another output impedance rating — such as 600 ohms — simply use that value resistor in the resistor under test jacks when making measurements with the signal generator.

Remember that the calibrated output value set displayed on many modern signal generators is for an output terminated as a matched load. Apply a 1-10 mV AC RMS test signal between



2 and 5 kHz to the input side of C1. The output voltage at U1, pin 6 or the node of R3 and C3 should be about 150 mV to 1.5 V AC RMS (± 20%).

To test the LT1357 U2 stage, unplug U1 and apply 1-10 mV AC RMS between 2 and 5 kHz to U1 pin 6. An input matching resistor (appropriate for your generator) can be spanned between U1, pin 6 and the TP1 common or U1, pin 3. You should observe about 20 times the input, or 18-180 mV (± ~10%) at U2, pin 6 or at the node of R9/C12. Note that while high level signal testing can be done with the can open (if your bench is not too noisy), for all actual noise measurements the can shield needs to be fully closed.

Calibration

Next, we calibrate the JCan for resistor noise. The good news is that the thermal noise from like valued resistors at zero current is about the same. Obtain a selection of several values of 1/4 watt metal film resistors from about 1K to 200K. One at a time, measure each resistor with your ohmmeter (or just read the printed value) and slide it into the resistor under test (RUT) posts in the JCan. I found it helpful to tape a label across each resistor as a tag with the resistor value. That way it was easier to read the value, and the tag doubled as a "pull" to help remove it from the test posts.

Close and lightly seal the JCan cover. Record the AC voltage as measured by a bench DMM, analog AC voltmeter, or an oscilloscope. It will be more difficult to make the measurements with an oscilloscope, but if that is the only instrument available to measure AC signals in a range of about 1 to 20 mV, go ahead and use it. It might work well to view an older analog CRT trace on a slower sweep speed and then divide the peak-to-peak voltage by a factor of about five.

Enter your R values and measured output voltages into an Excel spreadsheet or manual work sheet. (An Excel template can be downloaded from the *Nuts & Volts* website.) Note that the posted worksheet corrects the resultant thermal noise curves for the thermal noise floor of the JCan as the measured output value for a shorted input resistor under test. The worksheet also corrects the high end resistance values for the effective parallel resistance of the 10M JFET bias resistor. The calculated theoretical values for $\sqrt{Hz}$ thermal noise for each value use the well-known Johnson thermal noise equation:

$$Vnoise = \sqrt{4 \times k \times T \times R \times BW}$$

The JCan output for a shorted input should be on the order of 1 mV. Short the input posts and take a reading of your noise floor. Your measured noise floor can be directly plugged into the posted spreadsheet as the noise floor value in mV. To estimate the actual noise floor at the input, after later determining the JCan gain and effective noise bandwidth, return to this step and divide the noise floor at the output BNC (about 1 mV) by $\sqrt{BW} \times Gain$, where BW is the effective noise bandwidth and gain is the gain you measured with a 1 mV ACV RMS test signal at about 2 kHz. You can also estimate the amplifier noise by your measured data at the low end of the scale. The noise of the JCan front end circuitry adds with the resistor noise as a sum of the squares, or Solving for the JCan input noise:

$$V_{JCanOutput} = \sqrt{V_{Rnoise}^2 + V_{JCanInputnoise}^2}$$

There is some part-to-part variation in

$$V_{JCanInputnoise} = \sqrt{V_{JCanOutput}^2 - V_{Rnoise}^2}$$

JFET parameters, however with reasonably good construction practice, it should be possible to achieve an input noise value from about 2 to 4 $nV/\sqrt{Hz}$.

Plotting Data Without a Gain Measurement

If you do not have easy access to a signal generator, pick one entry in a range of about 10K-50K. Enter your total circuit gain into the gain number and your expected effective noise bandwidth (nBW) into the nBW cell or manually calculate the noise value by dividing the measured value by $(\sqrt{BW} \times Gain)$ to calculate the $\sqrt{Hz}$ noise value. Now adjust either the effective noise bandwidth or gain or both numbers until your experimental curve falls directly over the theoretical curve. Using this technique only the product $(\sqrt{BW} \times Gain)$ is defined, but that is good enough to be able to achieve a basic JCan noise calibration.

Plotting Data with a Gain Measurement

Terminate your input (RUT) with a suitable value for your signal generator. Apply 1 mV RMS at about 2 kHz to the input. Adjust the frequency slightly up and down to find the frequency at which you achieve peak gain (typically on the order of x2,600 to x3,200 or 2.6 to 3.2 VAC RMS) at the output for a 1 mV test signal. Enter the recorded gain number as the gain on the spreadsheet. Next, adjust the nBW number until the measured curves fall directly over the theoretical data at a mid resistance range of 10K-50K.

The (nBW) of a filter is equivalent to a "brick wall" filter of a flat gain and infinitely sharp roll off. The effective noise bandwidth is dependent on the shape of the frequency response of the actual filter and is not determined by the -3 dB point so commonly used to describe the voltage response with frequency. In fact, the effective noise bandwidth is determined using V^2, or power. Also, note that noise measurements do not necessarily require a steep filter response. It is only important that one be able to define the nBW for a given filter in terms of the equivalent brick wall filter.

If all has been done correctly to this point (by first measuring the JCan gain), the number you have just arrived at is the effective noise bandwidth of the JCan itself. This method of measuring nBW using only a small selection of resistors and a single gain measurement is far easier than more traditional techniques. One such method for determining the nBW of an audio filter is described in the sidebar.

HOW TO INDEPENDENTLY MEASURE THE JCAN EFFECTIVE NOISE BANDWIDTH

This independent test is an advanced measurement that can provide an independent determination of the JCan effective noise bandwidth (nBW). This measurement is not necessary for calibrating a JCan for basic noise measurements, which can be done using only a selection of resistors and the noise work sheet alone, or using a selection of resistors, a gain measurement, and the noise work sheet giving an additional determination of the nBW of the JCan.

The following procedure outlines the way we verified the operation of the JCan while developing and testing the project. To make this measurement, you will need a digitally controlled signal generator (or a counter monitoring a non-digital readout unit). Begin by setting the output signal level (possibly with the aid of an inline attenuator) to exactly 1.00 VAC RMS at your peak response frequency, probably about 2 kHz.

Starting at the lowest frequency on our spreadsheet, record the output voltage. (Note that if your input voltage is not constant with frequency, you will need to reset it at each frequency.) Enter the voltage into the voltage column. After all the data has been entered, notice that the spreadsheet squares each voltage number, then multiplies the average of that number and the one before it times the frequency interval. This results in a "piecewise integration" of the power curve.

A sum of all these slivers (a sliver is the thin vertical "slice" between each frequency value) of area under the curve is the effective bandwidth of the filter. Also, note that a setting of other than 1V AC output can be used by determining the peak output voltage and adding it into your calculations. There will be a technical note at **www.gellerlabs.com** discussing effective noise bandwidth in more detail.

If the experimental noise curve is lower on the high side of the resistive scale (80K-200K), it might mean that the input capacitance is too high. Note that we compensated for the effective parallel 10M bias resistor on our noise spreadsheet by recalculating all of the input resistances before doing the final noise calculation.

Once the input capacitance causes the bandwidth to fall below the designed effective noise bandwidth of approximately 20 kHz, the output voltage falls below that expected for a given resistance value under test. With good input circuit construction, it should be possible to accurately measure resistor noise out to 100K-300K full scale.

Our typical assembled JCan units have been found to have a total input circuit capacitance on the order of 3 to 4 pF. A socket initially used for Q1 was removed and replaced by pin jacks because the dielectric constant of the plastic in the socket added over 2 pF directly to the input capacitance.

Comparing Different Types of Resistors Under Power

Once the JCan is running and calibrated, it can be used to compare different types of resistors under a small test current. Locate a few sets of different types of resistors (preferably pairs of same resistance values). Try to include in your test group at least some old type carbon composition resistors. Note that it doesn't work to simply connect V+ to a single resistor under test. The problem is that for the AC input circuit, a resistance from V+ to the input capacitor is considered in parallel with a resistor under test from the gate capacitor to common. Thus, connecting V+ to a single resistor under test looks to the JFET gate like a short or near zero resistance!

To make the "power on" measurement, connect two same type, same value resistors in series. Connect a wire to the center tap (or lay out your test jacks) so the C1 JCan input connection is connected to the tap between the two resistors. The other end of one resistor goes to the same JCan input common jack used in calibration. The other end of the second resistor goes to +9V filtered power.

Note that for these tests, the value of R is the parallel combination of both like valued (same type) resistors. You should now see noticeably higher fluctuation in the output voltage since you are now looking at thermal noise plus resistor noise caused by current flow through the resistor. The additional noise includes shot noise as determined by the equation:

$$Inoise = \sqrt{2 \times q \times I \times BW}$$

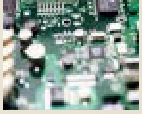
where I is the test current, q is the

PARALLEL AND SERIES RESISTORS UNDER TEST

Parallel and series combinations of resistors can also be tested. For a parallel combination, slide two 1/4 watt resistors into the slotted test jacks; for series connections, twist the ends of two resistors together or tack solder them. For larger leads, tightly wrap (like wire wrap) a small diameter wire on the end of the large lead to be able to slide it into the slotted test jack.

Notice that the noise from these combinations is the same as the noise expected from the equivalent resistance. At first glance, this seems counter intuitive since noise adds as the square root of the sum of the noise sources. The reason is that the measured output voltages are already representative of the mean square noise signals (noise power) and not the actual noise currents or voltages. The mean square signals are additive:

$$V_{JCanOutput} \propto \overline{V}^2_{TotalInputNoise} \times Gain_{JCan} \propto \overline{V}^2_{R_1} + \overline{V}^2_{R_2} + \overline{V}^2_{JCanInput\ noise}$$



charge of an electron, and BW is the effective noise bandwidth of the JCan and resistor “1/f” noise.

We use V+ filtered as the source of current for testing resistors under power. To test at a yet higher current, you could add a third 9V battery connected between V+ filtered (“V+ filt.” on the schematic) and the positive side resistor under test for 18V. Don’t go higher than 18V for powering the high side resistor under test, because even with the input capacitor, transients caused by connecting the resistors under test might damage the JFET.

If you are able to compare metal film resistors to carbon composition resistors, you can see that the noise is noticeably higher for the carbon composition resistors. One way to plot the noise data is to place colored dots on the calibration curves representing low and high fluctuation values for different types of resistors above the thermal noise for each resistor value on the resistance axis.

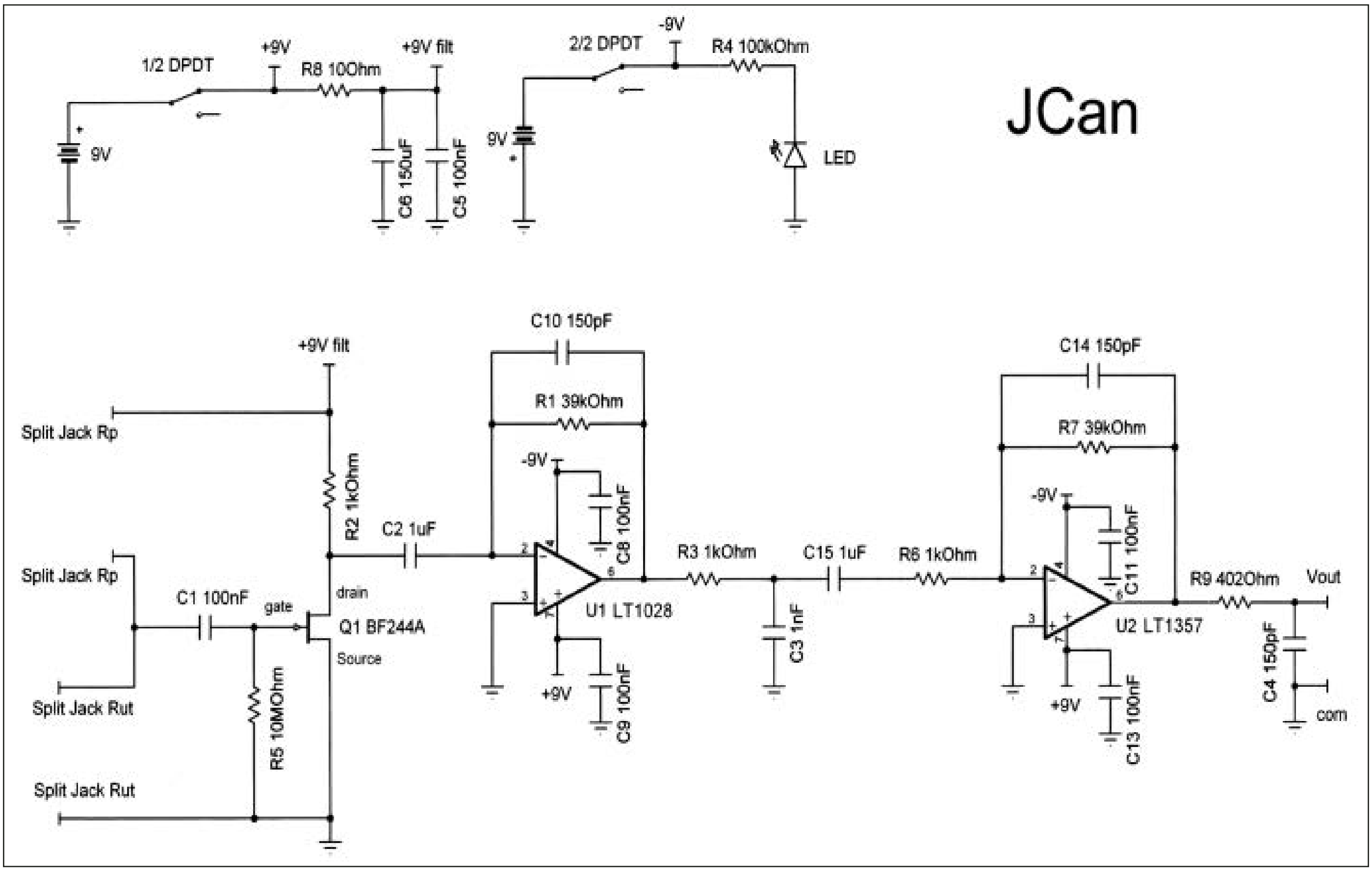
Another interesting experiment would be to see if you can detect the relatively small changes in noise with temperature. Usually to measure temperature, it is desirable to use a sensor with a relatively high rate of change of some measured parameter (usually resistance, voltage, or current). The opposite is true for resistor thermal noise, since thermal noise is proportional to $\sqrt{T}$, however, it should still be possible to measure changes in noise for changes in resistor temperature.

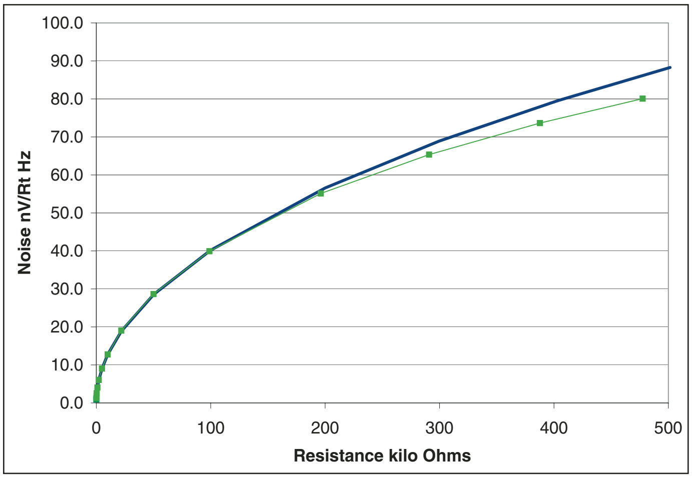
The easiest way to see the effect of a heated resistor — albeit at some risk to the fingers — is to heat a resistor and then plug it in, close the can, and observe the noise voltage drop as the resistor cools. If you use another resistor or a heat pump to heat or cool the RUT, you must remove all wires on the can before making the noise measurement. Otherwise, noise pickup from the heating or cooling wires acting as antennas can disturb the results.

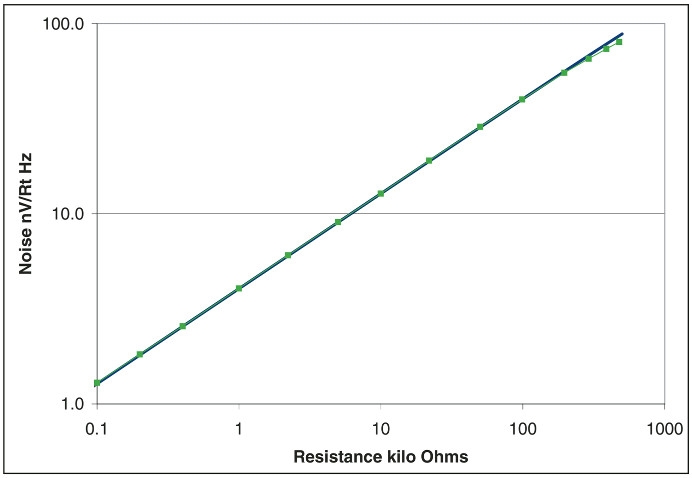
It is also probably not practical to heat the entire can, since the additional temperature effects on amplifier bandwidth and gain caused by the temperature coefficients of the amplifier resistors and capacitors would be difficult to determine. Another complication of temperature testing is to consider the temperature coefficient of the resistor, or its change in resistance with temperature, which also shifts the thermal noise voltage.

The JCan circuit might also be useful in other applications. As is, another circuit under test can be placed in the bottom of the JCan to make µV measurements on the second test circuit. Or, with some modifications, the Q1/U1 stage could be built into a small package for use as an active µV probe (long leads from the JCan would add too much capacitance). Yet another idea from Bill Jones, K8CU, is to reconfigure the RC filters for use as a low frequency, low capacitance antenna preamp for use with a short wire or whip antenna.

An interesting experiment would be to investigate the upper frequency limit of the preamp stages. With good



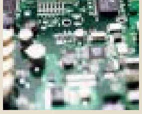




PARTS LIST

ITEM	QTY	REFERENCE	VALUE	DESCRIPTION
☐ 1	1	Q1	BF244A	Mouser 512-BF244A, Fairchild N-Channel JFET (you might want to buy 5 to 10 to observe differences between production JFETs).
☐ 2	1	U1	LT10281	Linear Technology Ultra low noise op-amp, Digi-Key LT1028CN8-ND, or Analog Devices AD797, Digi-Key AD797AN-ND
☐ 3	1	U2	LT1357	Linear Technology high speed op-amp, Digi-Key LT1357CN8-ND
☐ 4	1	Q1 Socket	Socket	Use pin sockets, same as item 14; a conventional transistor socket adds too much input capacitance.
☐ 5	2	U1,U2 Socket		Mill-Max DIP Low Profile, Mouser 575-193308
☐ 6	4	J1,2,3,4 Slit Socket		AMP gold #18 solder D-sub socket, Mouser 571-665693
☐ 7	1	R5	10M	We use Vishay VR25 BCC 5043D metal film resistor in our kits and assembled JCan, Mouser 594-5043DM10M00J (available only in large quantities). Also, RN1/4T1 1% 9.76M metal film, Allied Electronics 832-1111 or any other near valued 10M resistor (8M-10M, preferably metal film).
☐ 8	3	R2,3,6	1.0K	1% metal film, Xicon 1/4W (Mouser), For ex: Mouser ME271-1.0k (or, test and select for a V drain to source of about 4 or 5 volts).
☐ 10	2	R1,7	39.0K	1% metal film, Xicon 1/4W (Mouser)
☐ 11	1	R9	402 ohms	1% metal film, Xicon 1/4W (Mouser)
☐ 12	1	R8	10 ohms	1% metal film, Xicon 1/4W (Mouser)
☐ 13	1	R4	100K	1% metal film, Xicon 1/4W (Mouser)
☐ 14	9	Pin Sockets	SIP	We use a gold MILL-MAX pin jack, PN 0501-0-15-15-30-27-04-0; SIP type breakaway sockets, such as Mouser 575-643166 or equivalent, can also be used for R2, Q1, TP1, TP1 common, Vout, and Vout common.
☐ 15	2	C2,15	1 µF	Panasonic film capacitor, ECQV1J105M, Digi-Key P4548-ND
☐ 16	1	C1	0.1 µF	Panasonic film capacitor, ECQ-V1H104JL, Digi-Key P4525-ND
☐ 17	1	C3	0.001 µF (1nf)	Panasonic film capacitor, ECQ-B1H102JF, Digi-Key P4551-ND
☐ 18	3	C4,10,14	150 pf	AVX ceramic capacitor, 150 pf, 100V 10%, Digikey 478-3166-ND
☐ 19	5	C5,8,9,11,13	0.1 µF	Kemet ceramic, Mouser 80-C315C104M5U
☐ 20	1	C6	150 µF	Nichicon 150 µF, 50V, low impedance electrolytic, Mouser UHE1H151MPD
☐ 21	1	PCB		Geller Labs JCan PCB, www.gellerlabs.com
☐ 22	1	1/2 Gallon Paint		30W12A 1/2 Gallon "Short" Tin Can w/ Lid Unlined, 6-5/8" x 4", The Cary Company, 1195 W. Fullerton Ave., Addison, IL 60101
☐ 23	2	9V Battery Clips		Digi-Key 2240K-ND or equivalent
☐ 24	2	Double-sided Tape		3M 4013 1/2 wide foam mounting tape
☐ 25	2	Alkaline 9V Batteries		Rayovac 9V2 A1604-2 or equivalent
☐ 26		Resistors Under Test		A selection of metal film resistors from about 1K to about 300K for calibrating the JCan. We use the following collection in our "cal. pack": 49.9, 100, 200, 400, 1K, 2.2K, 4.9K, 10K, 22K, 49.9K, 100K, 200K, 300K, 402K, 499K. The exact values are unimportant. Actual values measured with an ohmmeter can improve your calibration data.
☐ 27		Resistors Under Test		A selection of different types of resistors, preferably in the range of 10K to 100K, such as carbon composition, carbon film, metal film, and wirewound for testing and comparing noise levels under power (one

continued ...



PARTS LIST continued ...

ITEM	QTY	REFERENCE	VALUE	DESCRIPTION
				resistor to V+ filtered and a like type and valued resistor from input to common); we use 82K to extend battery life.
☐ 28	4	4-40 Standoffs		General-purpose hardware (if you experiment with nylon, note that paint can common is made through one of the conductive metal corner posts).
☐ 29	4	4-40 Screws		General-purpose hardware
☐ 30	4	4-40 Nuts / Lock Washers		General-purpose hardware
☐ 31	1	DPDT Slide Switch		ITT (formerly C&K) 1201M2S3CBE2, Mouser 611-1201M2S3CBE2 or equivalent, 100,000 cycles, has an easy slide action.
☐ 32	1	BNC		AMP BNC bulkhead solder jack connector, AMP 31-10-RFX, Mouser 523-31-10-RFX
☐ 33	1	LED		Any LED visible at about 50 to 100 µA (to save battery life), some ultra brightness types work well.
☐ 34	1	RG-174		Short length of coaxial cable or (short) twisted wires made from the excess ends of the 9V battery clip wires

ACKNOWLEDGEMENTS

■ I would like to thank Dr. Richard Josephs of Innovative Instrumentation, Inc., for providing access to a Stanford Research Systems SR510 lock-in amplifier used throughout the development of the JCan prototypes and Warren Sarkinson for his valued advice and comments.

construction, the Q1 stage can perform out to 10 MHz, but the op-amp stages are limited to far lower frequencies by their open loop gain as a function of frequency.

Several people who tested the JCan design for us suggested listening to the output with an audio amplifier. Also, if you have a spectrum analyzer or digital oscilloscope with an FFT function, the noise spectra between different types of resistors under power is interesting to look at. The 1/f noise component can be directly seen as indicated by higher levels at the lowest frequencies.

Conclusion

We focused on building, testing, calibrating, and using a JCan to measure resistor thermal noise in this article. We touched on shot noise, using a small bias current to show the differences in noise between different types of resistors, such as metal film and carbon composition. We were not, however, able to provide a thorough or comprehensive introduction to the topic of noise, including Johnson thermal noise (white noise), 1/f "flicker" noise generally attributable to semiconductor crystal structures, or shot noise caused by current flow. A list of references on noise theory and application will be posted on **gellerlabs.com** including textbooks, articles, and web published university experiments, and semiconductor manufacturer tech notes. **NV**

JCan Noise Worksheet

LT1028 / LT1357

Legend:	Data Calculated by WrkSht	JCan calibration data	Entered Data

			Measured Data		
Enter Resistor Under Test (k ohms)	Corrected R for input R	Theoretical 1 Hz NBW nV calc	JCan Vout AC mV	JCan Vout AC mV corrected for input noise	1 Hz NBW calculated from JCan Vout nV / Rt Hz calc
0.052	0.05	0.9	**1.14**	0.4	0.9
0.1	0.10	1.3	**1.22**	0.6	1.3
0.1997	0.20	1.8	**1.36**	0.9	1.8
0.4003	0.40	2.6	**1.60**	1.2	2.6
0.9962	1.00	4.0	**2.17**	1.9	4.1
2.216	2.22	6.0	**3.02**	2.8	6.1
4.973	4.97	9.0	**4.36**	4.2	9.0
9.975	9.97	12.8	**6.06**	6.0	12.8
21.92	21.87	18.9	**8.96**	8.9	19.0
50.26	50.01	28.6	**13.43**	13.4	28.6
99.92	98.93	40.2	**18.69**	18.7	39.9
200.1	196.17	56.6	**25.78**	25.8	55.1
299.6	290.89	68.9	**30.56**	30.5	65.4
403.3	387.67	79.5	**34.43**	34.4	73.6
501.5	477.55	88.3	**37.44**	37.4	80.1

Enter JCan Gain	Enter JCan Bandwidth
3207	21234

Input R kilo ohms:	10000
Input Noise (mV at output)	1.06
Temperature degrees F	72.5

Calculated Temperature	
Centigrade	22.5
Kelvin	296

REFERENCES

■ 1) J.B. Johnson, "Thermal Agitation of Electricity in Conductors," *Physical Review*, vol. 32, July, 1928, page 97.

■ 2) Horowitz and Hill, "The Art of Electronics," Cambridge University Press, 1986, Section 7.10, "Origins and Kinds of Noise," pages 288-290.

■ 3) Ibid., Section 7.20, "Bandwidth Limiting and RMS Voltage Measurement," page 306.

■ 4) B. Klein, N. Albaugh, "Analog eLab: Amplifier Noise: Types, Origins, Magnitude Predictions and Reduction Techniques," March, 2005, a TI Webcast at **www.ti.com**.