Designing for Ultra-Low THD+N (Part 1)

Understanding Measurable Noise and Distortion

By
Bruce Hofer
(United States)

The design of ultra-low-noise, low-distortion circuits is more than simply a matter of a well-considered schematic. Because of their impact on measurable noise and distortion, layout and component quality are often more important.

Let me clarify up front what may be a misconception. This article is not about what makes the "best" audio amplifier nor do I make any claims about audible quality. I shall leave those subjective matters to others, and instead focus on what we at Audio Precision have been doing for many years: understanding what is in fact measurable and what mechanisms contribute to the imperfections we find.

Few audio products qualify as "Ultra-Low THD+N" and for most purposes this is perfectly acceptable. But for those who work in this rarefied environment, only a select set of tools can reveal behaviors that separate the merely good from the truly remarkable and a deep understanding of circuit behaviors is required to address and improve the designs produced. This means moving beyond the approximate representation of Maxwell's equations encapsulated in a schematic and focusing on the actual circuit's physical implementation.

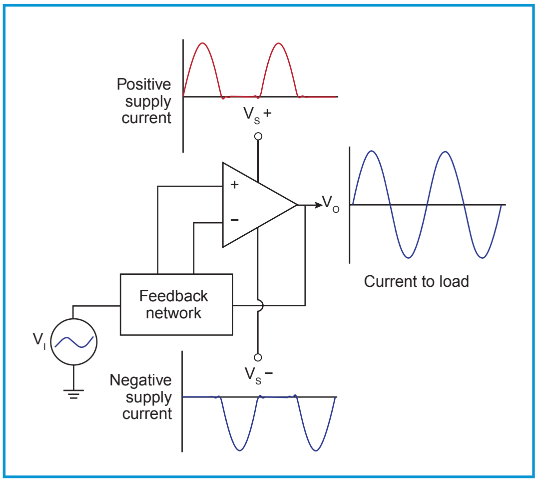


Figure 1: The op-amp supply currents look fine in the schematic; however, Lenz's law indicates there may be a problem.

Is Circuit A Better Than Circuit B?

After many years in the audio business, you observe trends and ideas that become popular among designers for certain time periods. These trends often take the form of circuit types, some of which claim to solve specific problems or to somehow "sound better" than others. While some designs are genuinely clever and may address certain issues (e.g., circuit protection) most do not become canonically accepted as "the best" for audio because actual implementations reveal a range of behaviors from product to product. The magic bullet is only magic in a suitable context. It is otherwise unremarkable. Circuit A is only better than circuit B when circuit A is realized with the appropriate attention to detail, and roles may easily be reversed with decisions around bias, compensation, component quality, layout, and so forth.

Lenz's Law's Unintended Consequences

We all recall learning the basic physics of electricity in high school and college. We know from the earliest lessons that a conductor's current flow generates a magnetic field, and conversely that magnetic fields may induce potentials in nearby conductive loops. While we use this explicitly in the design of transformers, motors, and loudspeakers, it is a fact often obscured by the approximation of electromagnetic systems represented in electronic schematics. When exploring extremely low levels of THD+N, these approximations become very important to understand.

Consider an op-amp. This common amplifier employs a Class-AB output, and when configured with feedback can deliver a very linear current to a

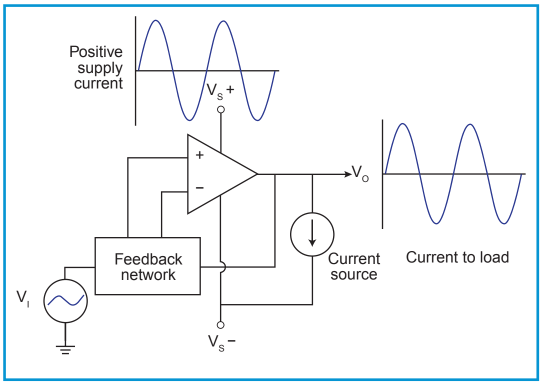


Figure 2: The op-amp is forced to Class A and only one rail is used.

load. Since all current is being provided by the supply rails, you may assume that the supply current is likewise very linear with respect to the input signal. This would be incorrect and has measurable consequences.

Since the op-amp's output is Class-AB, the output transistors are transitioning from OFF to ON states in a somewhat complementary fashion, responding to changes in the input signal. This means that each supply rail ($-V_S$ and V_S) delivers a current waveform that contains a rectified version of the total output current superimposed on the DC value (see **Figure 1**).

Why Is This a Problem?

Here is where Lenz comes back to us with mutual inductance. In the real world, Lenz's law tells us that currents generate magnetic fields around conductors that in turn generate potentials in adjacent conductive loops. If these currents contain distorted representations of the signal, then this distortion may well "bleed" into other stages (e.g., the feedback path) and become measurable as a function of frequency. This has nothing to do with the amplifier's schematic, per se.

At higher currents, this can seriously affect measurements. As a result, power amplifiers often demonstrate relatively high levels of this form of distortion at higher frequencies. This occurs regardless of quality of components or circuit design on paper. It is a result of high currents injecting nonlinear signals via mutual inductance to other loops within the amplifier and is more a function of physical layout than schematic. This behavior may even be *the* dominant distortion product in otherwise very high-quality amplifiers.

Does this mean that this problem is immediately audible? No, but in the world of extremely low THD+N, we must consider sources of nonlinearity that others ignore. We must look very carefully at the schematics and the physical layout to understand this.

Planes and Traces

When is more ground not such a good thing? The answer is: when you don't know where the currents are.

Some designers favor the use of a solid "power supply plane" as a PCB layer. As such, a plane certainly appears to be an effective way to carry a large amount of current and hence will reduce problems of interference from the perspective of relative voltages. There is very little measurable resistance and thus few voltage variations at different points on the plane.

But the currents, visible or not, must follow a specific set of paths from point-to-point along this plane. The flow will not be evenly distributed but will follow, literally, the path of least resistance, however small the difference. Lenz's law still applies, which means that noisy currents flowing across the plane may still induce signals into other areas of the circuit, only now we have no means to control these effects by moving traces. For this reason, well-designed traces are preferable to supply planes in ultra-low THD+N designs, as they give the engineer control over precisely where current flows and hence where noise and distortion can be injected.

Isn't This an RF Problem?

While the previously described phenomena are more pronounced as $f \rightarrow \infty$, the higher currents involved in power amplifier design mean that these effects can be easily

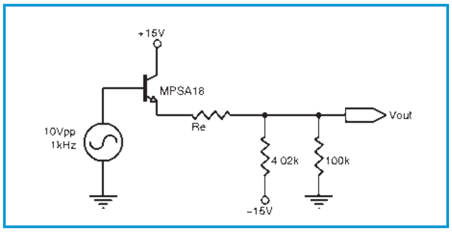


Figure 3: A simple emitter follower was constructed using a MPSA18 transistor.

7052PH
PHANTOM Powered
Measurement Mic System
NOW 4Hz to 25+kHz
<16dBA >135dBSPL
IEC61094-4 Compliant
1dB/div
Anechoic Free Field Response Included
Rugged STAINLESS Body
Operational
<-20 to >70C
Storage
<-30 to >85C
PHANTOM
<18Vdc to >56Vdc
Removable Capsule Titanium Diaphragm
www.acopacific.com

About the Author

Bruce Hofer is a co-founder of Audio Precision and a widely respected analog design expert with a career spanning more than 40 years. His designs rank among the quietest and lowest distortion audio measurement circuits in the world.

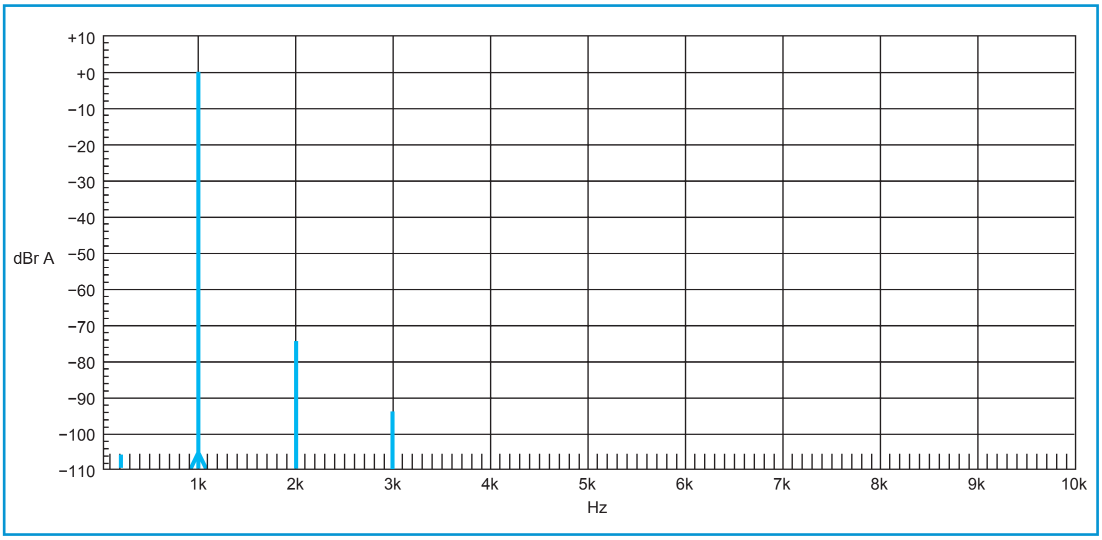


Figure 4: Emitter follower distortion measurement shows R_E = 4.02 k, V_S = ±15 V, and Vsignal = ±5 V_{PEAK} at 1 kHz.

measured at frequencies as low as 5 kHz. It is precisely that attention to detail that separates the good from the great at the extremes of performance.

Some Partial Solutions with Op-Amps

Op-amps are at the heart of much analog audio. Some useful techniques can help reduce the problems mentioned here.

Decoupling

Ensure that power supplies are differentially decoupled as physically close to the op-amp as possible to minimize loop area. The nonlinear AC supply currents will be shunted to each other, thus reducing unwanted induced potentials.

Forcing Class-A Operation

Another partial solution to rectified supply currents is to force op-amp output stages to run (nearly) Class A by loading the output to a rail, forcing only one rail to be used all the time (see **Figure 2**). Currents will be more linear but, of course, the op-amp now is expending more energy and has reduced output capacity.

Estimating Semiconductor Distortion Contributions

While the use of op-amps with abundant feedback negates much of the need to worry about the nonlinearity of discrete transistors, there are still many cases in which discrete designs are desirable. These nonlinearities are significant and can be well estimated before prototyping.

A Taylor series approximation works well to estimate distortion from certain forms of nonlinearity (e.g., the behavior of semiconductor junctions. However, it does not generalize to all forms of nonlinearity (some nonlinearity forms will be discussed in our next article).

Use a Taylor Series to Model Nonlinear Behavior in Semiconductor Junctions

The circuit is modeled as having a voltage dependent gain:

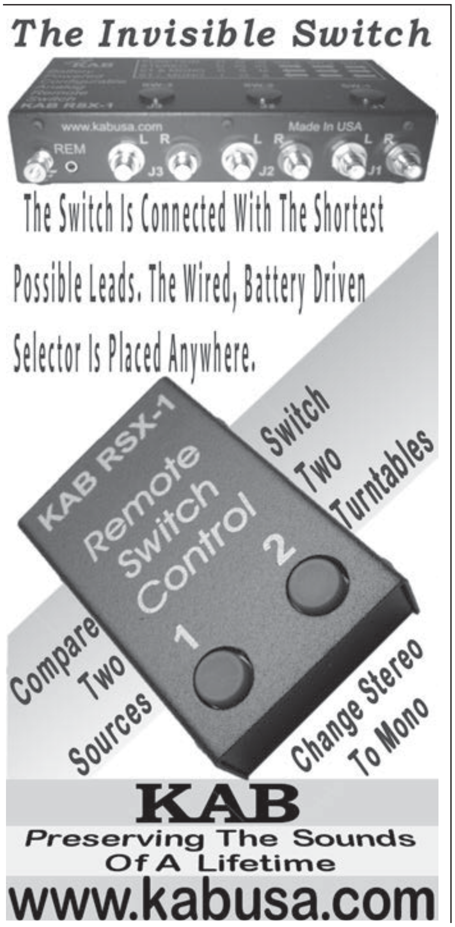
$$\frac{V_{OUT}}{V_S} = f\left(V_S\right) = A_0\left(1 + V_S k_2 + V_S^2 k_3 + \dots\right)$$

The second (2HD) and third (3HD) harmonic ratios can be estimated with surprising accuracy using only three values for dynamic gain at the positive peak (A_P), negative peak (A_N) and, zero (A_0) points of an assumed sine-wave signal:

$$2HD \approx \left(\frac{k_2}{2}\right) = \frac{\left|A_P - A_N\right|}{8A_0}$$

$$3HD \approx \left(\frac{k_3}{4}\right) = \frac{\left|A_P - A_N - 2A_0\right|}{24A_0}$$

Note that 2HD (as a ratio) is proportional to V_S, while


The Invisible Switch
The Switch Is Connected With The Shortest Possible Leads. The Wired, Battery Driven Selector Is Placed Anywhere.

KAB
Preserving The Sounds Of A Lifetime
www.kabusa.com

3HD is proportional to V_S^2. Since these first harmonics will dominate overall distortion, they are sufficient for estimation purposes.

Emitter Follower Distortion

We constructed a simple emitter follower using a MPSA18 transistor with R_L = 4.02 k wired to –15 V and the collector to 15 V (see **Figure 3**). Performance with a ±5 V_{PK} (10 V_{PP}) signal is to be determined at 21.8°C (≈295 K).

- The 100-kΩ load resistor represents the input impedance of the audio analyzer (DC coupled)
- The element "R_E" models the dynamic impedance of the emitter-base junction. "R_E" interacts with the total load impedance to provide a voltage gain that is slightly less than unity and that varies as a function to the instantaneous signal voltage.

Dynamic emitter impedance, $R_E \approx kT/qIe$
"k" = Boltzmann's constant = 1.38065×10^{-23}
"T" = 295K (ignoring self heating within the transistor)
"q" = electron charge = 1.6022×10^{-19}
Gain is calculated at VB = –5, 0, and 5 V:

$$V_B = -5\text{ V}: I_E = 2.282\text{ mA}, R_E = 11.138\ \Omega \therefore A_N = 0.099713$$

$$V_B = 0\text{ V}: I_E = 3.576\text{ mA}, R_E = 7.1085\ \Omega \therefore A_O = 0.099816$$

$$V_B = 5\text{ V}: I_E = 4.870\text{ mA}, R_E = 5.22\ \Omega \therefore A_P = 0.099865$$

Hence:

$$2HD \approx \left(\frac{k_2}{2}\right) = \frac{|A_P - A_N|}{8A_0} = 0.019\%\ (-74.4\text{ dB})$$

$$3HD \approx \left(\frac{k_3}{4}\right) = \frac{|A_P - A_N - 2A_0|}{24A_0} = 0.0023\%\ (-92.8\text{ dB})$$

The Envelope, Please

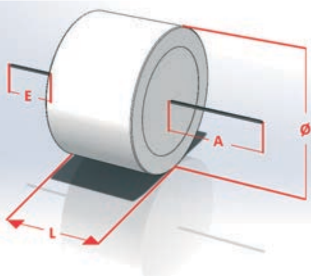
How well does this technique work? The measured levels of 2HD and 3HD with a 10-V_{PP} sine wave at 1 kHz are –75.1 dB and –93.4 dB compared to the estimates of –74.4 dB and –92.8 dB, for a difference of 0.7 dB and 0.6 dB, respectively (see **Figure 4**).

This estimation method can be used to analyze distortion contributions for any semiconductor junction in a design and can be used to help identify separate contributions from other sources, such as those discussed in the earlier sections.

Next Up

In my next article, I will discuss the importance of resistors and capacitors in ultra-low THD+N designs. The conclusions may surprise you.

EVOLUTION
through INNOVATION



The main feature of the EVO winding technology comes with its unusually narrow but high capacitor reel. This geometry results in two, acoustically clearly perceptible benefits: A much shorter and utmost little loss signal path between huge contact areas is granted, thus an extremely low equivalent series resistance/ESR. Secondly, in order to meet capacitance the number of paralleled windings is larger than with regular caps, thus an effectively minimized equivalent series inductivity/ESL.

After the utterly precise EVO winding process, these reels are spilled by hand in especially developed MCap*housings. By that, vibrations and microphonic effects on the reel are most effective avoided. Furthermore, we only employ purest Polypropylene foil vaporized with thickest metal layer possible. Plus the unusual asymmetric wire lengths allow both mounting girections on PC boards, horizontal and vertical.

Now available: MCap®EVO • MCap®EVOAlu.Oil
MCap®EVOSilverGold.Oil

MUNDORF®

Mundorf EB GmbH
Liebigstr. 110
50823 Köln • Germany

+49 221 977705-0
info@mundorf.com
www.mundorf.com

Designing for Ultra-Low THD+N (Part 2)

Resistors and Capacitors

By
Bruce Hofer
(United States)

The first article in this series described how factors beyond the schematic can effect an audio circuit design's real-world performance. This article examines the most common passive components on a circuit board—resistors and capacitors. This article's focus is not what makes the "best" audio amplifier nor do I make any audible quality claims. I shall leave those subjective matters to others. Instead, I will discuss what we at Audio Precision have been doing for many years—understanding what is in fact measurable and what mechanisms contribute to the imperfections we find.

Resistors in Analog Design

Resistors come in many forms, incorporating several different technologies, and they are available at many different price points (see **Photo 1**). The primary types used in audio include: carbon composition, thick film, thin film or metal film, metal foil, and wire wound.

To one degree or another, all of these constructions exhibit two primary types of nonlinearity: voltage coefficient and power (thermal) coefficient.

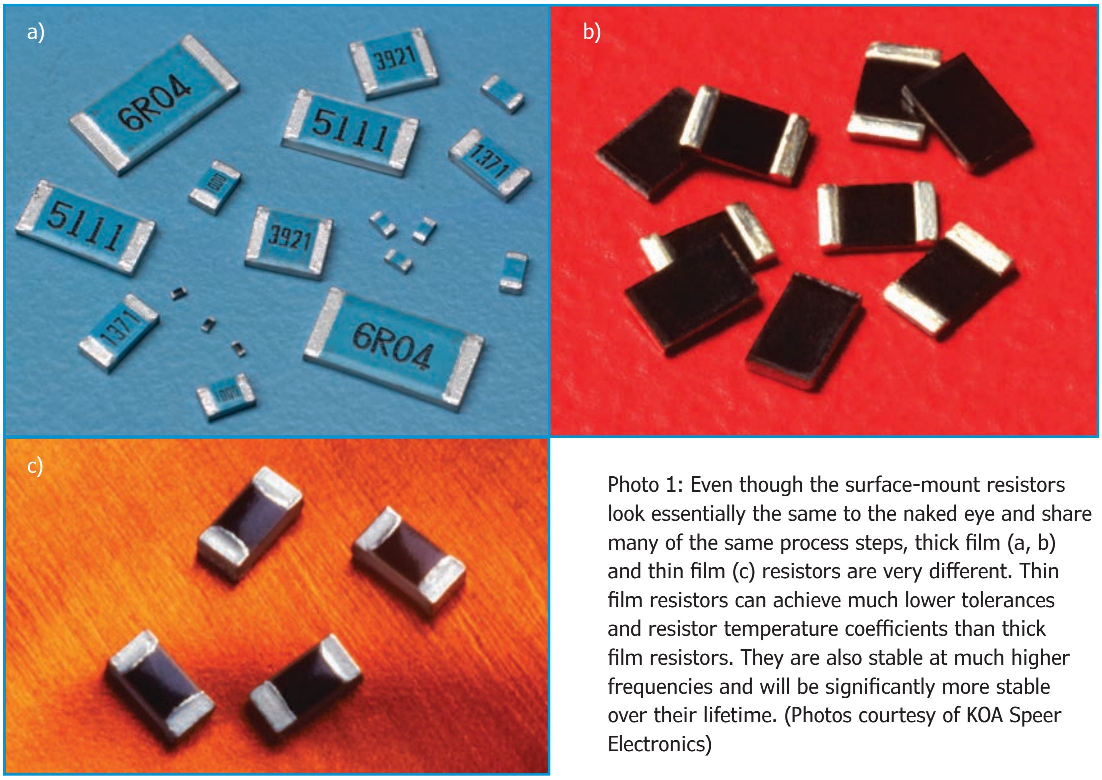


Photo 1: Even though the surface-mount resistors look essentially the same to the naked eye and share many of the same process steps, thick film (a, b) and thin film (c) resistors are very different. Thin film resistors can achieve much lower tolerances and resistor temperature coefficients than thick film resistors. They are also stable at much higher frequencies and will be significantly more stable over their lifetime. (Photos courtesy of KOA Speer Electronics)

I'll discuss how each can be modeled and how this can affect ultra-low THD+N designs.

Defining Resistor Terms

Resistor Temperature Coefficient—All resistors exhibit value changes as a function of temperature. The temperature coefficient of resistance (TC_R) describes the magnitude of this sensitivity and is expressed in units of parts per million per degree C (ppm/C).

In addition to the TC_R's static (DC) values, there is also a dynamic component, which is the result of temperature changes propagating through a resistor as a function of time. This function is often referred to as the resistor power coefficient, as it represents the effects of temperature changes caused by the dissipation of energy in the resistor as a result of applied signals.

Resistor Voltage Coefficient—In addition to changes in value due to temperature, a resistor's value may also change as a function of applied voltage. The voltage coefficient of resistance (VC_R) describes the magnitude of this effect for a given resistor.

The value is expressed in units of parts per million per volt (ppm/V). This value is generally positive and results in a decrease of resistance as applied voltage increases.

Resistor Type Summary

All resistors are not created equal. There are many types of resistors, each with distinctly different behaviors.

Carbon Composition Resistors—A carbon composition resistor's resistive element is a compact mixture of carbon and ceramic held together in a resin base.

Experienced readers will recall that prior to the 1970s, carbon composition resistors were extremely common. This is not true today and for good reasons. Carbon composition resistors usually have poor tolerance (typically 5% to 20%); poor TC_R (typically 150 to 1,000 ppm/C)—and worse at lower values. These resistors also have high modulation noise and high VC_R compared to other types

While still useful in some non-audio applications, carbon composition resistors are *not* recommended for high-performance analog designs. One interesting audio exception is the vacuum tube guitar amplifier design, in which the distortion characteristics of early eras are still prized.

Thick Film Resistors—A thick film resistor's resistive element is a conductive film applied to the surface of a cylindrical or rectangular substrate. Resistance is determined by the film composition and the etching pattern.

This type of resistor is currently popular for general-purpose applications. It offers much better performance than composition type resistors. Thick film resistors have good tolerance (0.1% to 2%), good TC_R (typically 100 to 250 ppm/C), adequate VC_R (it varies considerably from brand to brand, but it can be as high as 10 ppm/V), and adequate modulation noise.

Thin Film (Metal Film) Resistors—Thin film resistor's resistive element is a stable conductive film that is sputtered onto the surface of a cylindrical or rectangular substrate. Resistance is determined by film thickness and pattern.

Thin (metal) film resistors offer superior performance when compared to their thick film counterparts, but at much higher cost. Thin film resistors offer excellent tolerance (0.02% to 1%), excellent TC_R (which is typically 5 to 25 ppm/C but it can be as low as 2 ppm/C), excellent VC_R (between 0.1 and 1.0 ppm/V), and excellent modulation noise.

Metal Foil Resistors—A metal foil resistor's resistive element is a special alloy metal foil that is the cemented to an inert substrate. Resistance is determined by foil characteristics and pattern. Trimming is accomplished by opening links in the foil pattern, which is more stable than "L" cut trimming.

Metal foil resistors feature the best performance at DC. They are also the most expensive. Metal foil resistors offer outstanding tolerance (as low as 0.001%), outstanding TC_R (as low as 0.05 ppm/C), outstanding VC_R (typically less than 0.1 ppm/C), and extremely low modulation noise.

However, praise for metal foil resistors comes with a caveat. Their low-frequency modulation distortion can be much worse than expected.

Wire-Wound Resistors—The resistive element for a wire-wound resistor is a wire with a low-temperature coefficient that is carefully wound on a substrate. Its resistance is determined by the wire's composition, length, and thickness.

Wire-wound resistors are typically appropriate only for smaller resistance values, but they can support high peak and average power ratings. They exhibit almost no VC_R, but due to the combination of low values, stray inductance, and other parasitic effects, they are uncommon in modern audio circuits.

Resistor Nonlinearity

Resistors exhibit nonlinearity from two sources: the voltage coefficient and the power (thermal) coefficient. To understand the differences, I will explain

About the Author

Bruce Hofer is a co-founder of Audio Precision and a widely respected analog design expert with a career spanning more than 40 years. His designs rank among the quietest and lowest distortion audio measurement circuits in the world.

how these are modeled.

Resistor Voltage Coefficient Nonlinearity—In most common electronics designs, the VC_R is safely assumed to be negligible. This is not the case when designing ultra-low THD+N devices. Note that while VC_R and the subsequent TC_R are correlated as a matter of practice, they represent wholly separate phenomena, which must be taken into account.

The model commonly used for voltage coefficient nonlinearity is dependent on the applied voltage, as shown below:

$$R(V_S) = R_0 \times (1 - VC_R \times |V_S|)$$

Because this model employs the absolute value of the applied voltage (V_S), use of a Taylor series is not appropriate. However, we can estimate the distortion by taking the fast Fourier transform (FFT) of the product of a sinusoidal signal multiplied by a full-wave rectified version of itself (e.g., the FFT of sin(ωt) × | sin(ωt)|). In this case, it follows that:

$$2HD \approx 0$$

Assuming no significant DC component, and thus:

$$3HD \approx \frac{|VC_R \times V_S|}{5.9}$$

Note the proportionality to V_S and not V_S^2 as might be expected if you used a Taylor series model for nonlinearity.

$$5HD \approx \frac{|VC_R \times V_S|}{41} \approx \frac{3HD}{7}$$

In other words, the fifth harmonic's magnitude is estimated to be approximately –17 dB below the third harmonic. It is clear that nonlinearities due to this mechanism are dominated by the third harmonic's presence.

Resistor Power Coefficient Nonlinearity—The nonlinearities that arise from power dissipation in a resistor are a result of temperature changes, forming a correlation between applied signals and the TC_R. Simply looking at a static model of the power coefficient, we can model this as:

$$R(P_S) = R_0 \times (1 + k_P \times P_S)$$

Where k_P is our power coefficient and P_S is the power being dissipated by the resistor. The power coefficient is expressed in units of ppm/W and may be either positive or negative.

Resistor Thermal Modulation Nonlinearity—The power coefficient model is a static description of the effects of internal heating due to an applied voltage. In ultra-low THD+N analog design, nonlinearities that are correlated with changes in signals can affect the outcome.

Because a resistor cannot instantaneously dissipate heat, the effects of thermal changes due to applied signals are complex functions of frequency that are highly dependent upon resistor size, placement, and construction. Thermal modulation can be modeled as follows:

$$R(V_S) = R_0 \times \left[1 + TC_R \times Z(\omega) \times \left(\frac{V_S^2}{R_0}\right)\right]$$

Where Z(ω) is the device thermal impedance as a complex function of frequency. As ω -> 0, | Z(ω)| -> θR, or the DC thermal resistance.

Thermal Modulation at Very Low Frequencies—At very low frequencies (typically less than 0.2 Hz), the resistor reaches thermal equilibrium as quickly as the signal varies. The model can be used to predict:

$$2HD \approx 0$$

A True Story of Resistance

About 13 years ago, a certain manufacturer changed its network substrate material from ceramic to passivated silicon without notifying customers. Ceramic is brittle. It is also more expensive to process and cut to size, and the company was hoping to save money.

Although the resistor DC parameters remained unchanged, the AC performance proved to be disasterous. The stray capacitance between each resistor and the substrate was higher and nonlinear. It is believed that P-I-N diodes were formed between each resistor and the semi-conducting substrate, thus causing the voltage drop in one resistor to generate distortion products in the other resistors!

The manufacturer quickly added the "option" to specify the original ceramic substrate when told it was about to be disqualified by key customers.

Assuming no significant DC bias:

$$3HD \approx \frac{TC_R \times \theta_R \times \frac{V_S^2}{R_0}}{4}$$

$$5HD \approx 0$$

Contrast this with 5HD ≈ 3HD/7 for the resistor voltage coefficient distortion.

Thermal Modulation at Low Frequencies—Within the 5-to-200-Hz range, the magnitude of Z(ω) is usually (though not always) much smaller than θR, rolling off to near zero above 1 to 5 kHz.

There are exceptions. My recent experiments (which are also corroborated by another individual) show that some metal foil resistors with exceptionally low TC_R behave as if | Z(ω)| >> θR, thus contributing higher modulation distortion than a thin film resistor with a larger TC_R under identical conditions.

Controlling the Effects of Resistor Nonlinearity in Audio Circuits—The mechanisms previously described may have measurable effects on audio circuits.

Resistor Voltage Coefficient Effects—Even low VC_R values can introduce measurable distortion. Consider a single feedback resistor in an amplifier producing a 50-V output, which is not an uncommon value in higher power designs. Even if this resistor provides a respectable 10 ppm/V VC_R, it is now contributing 0.05% distortion, which is very significant.

Now, consider that there are many resistors in the circuit, all contributing in varying ways and degrees. Wisely choosing resistors can make a real difference in your design's quality.

Reducing Voltage Coefficient Nonlinearity—Use thin film resistors for most applications. These resistors are much better than thick film with regard to VC_R by a factor of 5 to 10. Never use carbon composite resistors, unless high amounts of VC_R distortion are desired.

Using multiple resistors in series can significantly reduce problems associated with VC_R. A string of n identical resistors in series reduces the applied voltage across each to V/n, thus reducing the effect of any VC_R nonlinearity.

Resistor Temperature Coefficient Effects—As I discussed earlier, the thermodynamic behavior of resistive elements means that a resistor cannot instantaneously change temperature as the signal across it changes. It acts as a low-pass filter for temperature change.

At DC, there is not a problem with regard to linearity as the resistor is nominally at thermal equilibrium. Likewise, at very high frequencies any changes occur so rapidly that the low-pass filtering effect of the resistor's thermal behavior results in an even temperature distribution across the element.

Problems occur in a middle zone of approximately 5 to 200 Hz. In this range, the resistive element's temperature may vary with time as a function of signal. It may also vary as a function of location within the resistor itself. The result can be significant and measurable distortion at those low—and often audible—frequencies.

Making matters worse from an audio perspective, the temperature coefficient's effects are proportional to the signal's absolute value applied across the resistor. This means the resulting distortion is dominated by third harmonics—a very audible variety of distortion that occurs in a high hearing sensitivity area.

Reducing Temperature Coefficient Nonlinearity—Avoid the common 25-ppm/C characteristic in critical circuit locations. Instead, opt for premium parts that deliver 10-ppm/C or even 5-ppm/C characteristics.

Avoid metal foil resistors. While they have very low temperature coefficients (less than 1 ppm/V), they exhibit poor AC performance. This information isn't found in the datasheets, which typically only show DC values.

For surface-mount technology (SMT) resistors, only use the 1206 size. Smaller resistors exhibit increasingly larger dynamic thermal impedances, thus exacerbating signal-dependent nonlinearity for ultra-low THD+N audio.

Limit the signal across resistors to approximately 20 mWpk or about 3 VRMS (12 dBu) for the lowest distortion. Also, use series-parallel combinations in circuits requiring higher peak power dissipation or higher voltage.

Resistor Networks—Resistor networks

The Convenient All-in-One Solution
for Custom-Designed Front Panels & Enclosures

You design it
to your specifications using our FREE CAD software, Front Panel Designer

We machine it
and ship to you a professionally finished product, no minimum quantity required

- Cost effective prototypes and production runs with no setup charges
- Powder-coated and anodized finishes in various colors
- Select from aluminum, acrylic or provide your own material
- Standard lead time in 5 days or express manufacturing in 3 or 1 days

FRONT PANEL EXPRESS
FrontPanelExpress.com
1(800)FPE-9060

Photo 2: Mechanical resonance is a key feature in audio capacitors, which come in a variety of types and sizes. (Photo courtesy of Humble Homemade Hifi, www.humblehomemadehifi.com/Cap.html)

offer extremely low differential temperature coefficients. They are especially useful in applications that benefit from precise ratio matching.

Ratio accuracy can be as good as 0.01% for thin film and 0.001% for metal foil. Watch for high thermal modulation effects with metal foil resistor networks.

Avoid large ratios of R (e.g., 10:1 or higher). The best performance is achieved when all resistors are of equal value.

The small size of some resistor networks (e.g., SOIC-8/-16) means a higher thermal impedance such as Z(ω). The result is higher thermal modulation distortion than discrete resistors.

Reducing Noise from Resistors—Resistor noise voltage is proportional to $\sqrt{R}$ and to $\sqrt{T}$. Hence, a low-noise analog circuit design implies the use of the lowest possible resistor values that are consistent with power dissipation and distortion requirements and circuit topologies that inherently minimize the value of resistors in the signal path. Use only thin film or metal foil resistors when they must pass significant DC bias currents.

Capacitors in Analog Design

Capacitors are used for AC coupling and signal EQ in analog designs. While many people may think that coupling capacitors contribute little or nothing to an audio signal's quality, this is not true. Poor choices in the selection of coupling capacitors can have a dramatic effect on an analog design's performance.

Like resistors, capacitors are implemented in a variety of ways to meet goals of cost, behavior, and

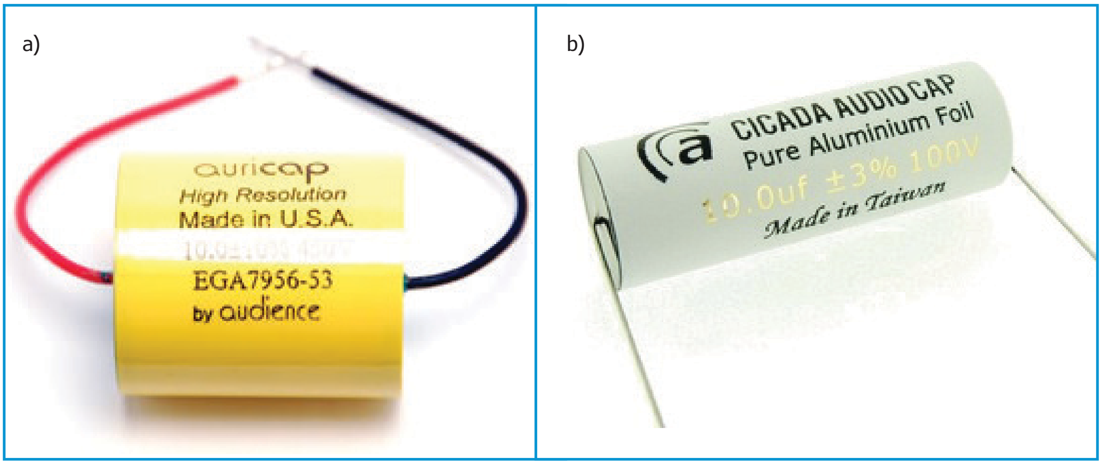


Photo 3a: Auricap metalized Polypropylene capacitors are cylindrically wound with epoxy end fill. b) Cicada Pure Aluminium Foil 100VDC type MKP (Photo courtesy of Humble Homemade Hifi, www.humblehomemadehifi.com/Cap.html)

performance (see **Photo 2**). The common types of dielectric materials found in audio signal paths are: polymer film (PET, PEN, PPS, PP, PS, and PTFE), ceramic (Z5U, X7R, NP0, and Hi-K), mica, and glass.

Polymer File Capacitors—There are many types of polymer film capacitors (see **Photo 3a**). Polystyrene (PS) provides excellent performance with a low temperature coefficient (approximately 100 ppm/C). However, it has a low melting point (85°C), which can result in damage due to soldering. Polypropylene is often an attractive alternative with a higher melting point (105°C) but it also has a higher temperature coefficient (up to 250 ppm/C).

Metalized Film vs. Film-Foil Construction Capacitors—The primary difference between polymer file capacitors with regard to ultra-low THD+N designs concerns the construction.

Film-foil capacitors (also called metal foil) are made using two plastic films as the dielectric. Each film is coated with a thin metal foil that acts as the electrodes (see **Photo 3b**).

Metalized film capacitors also use a plastic film as a dielectric, with electrodes formed by vacuum-depositing aluminum on one or both sides of the film. Film-foil capacitors exhibit lower equivalent resistance and support higher current surges. If possible, select only film-foil types for signal path use in audio designs.

Ceramic Capacitors—With one notable exception, ceramic capacitors are not suitable for use in high-performance analog design, as they exhibit very high voltage dependent nonlinearities.

The exception is the "NP0," or "COG" type of ceramic capacitor. These boast low dissipation factors and frequency dependences. They also have low temperature coefficients (30 ppm/C specified, 15 ppm/C typical). They are extremely stable and virtually immune to humidity.

NP0 types are available in values up to 100 nF with voltage ratings up to 500 V. To achieve higher values and the best performance, consider paralleling multiple NP0 capacitors and avoid ones rated at 25 V. The larger voltage rated capacitors (i.e., 50 and 100 V) are not much larger and offer superior linearity.

In addition to common nonlinearities, certain low-grade ceramic capacitors (e.g., Z5U, Y5Y, and Hi-K) can exhibit strong piezoelectric effects. This means that mechanical stresses on the capacitor can induce voltages across itself, which is something to be avoided at all costs.

Mica Capacitors—Long ago, mica capacitors were highly regarded for analog design, but this is no longer true. While mica offers good stability, it is a product of nature for which the better sources are now depleted. With the availability and lower temperature coefficient of NP0 (COG) ceramic capacitors, there is simply no good reason to specify a mica capacitor.

Glass Capacitors—Glass is among the most stable and inert of dielectrics, with virtually no aging and a near-zero voltage coefficient. However, glass exhibits a higher temperature coefficient than NPO ceramics and is difficult to form with great accuracy, resulting in typical tolerances of 5%. Values of 1% to 2% are available, but extremely expensive.

Microphonic Effect in Capacitors—In any capacitor:

$$dQ = d(C \times V)$$

This equation is often simplified to:

$$I = C \times \frac{dV}{dt}$$

However, "C" itself is not necessarily constant. It may vary as a function of voltage and mechanical stress, can be captured as:

$$I = C \times \frac{dV}{dt} + V \times \frac{dC}{dt}$$

The clear insight to draw from this is to minimize the DC potential across all capacitors in series with the signal path.

Details Matter

Ultra-low THD+N does not occur by accident nor does it manifest purely in schematic diagrams. It is the result of careful attention to detail, clever circuit design, and the selection of high-quality components that are appropriate for each specific job.

AIRBORNE

THE WINGS OF MUSIC

Airborne is proud to introduce a new line of Air Motion Transducers and Ribbon Tweeter. Including the smallest AMT in the world and an open back type Planar Ribbon.

AMT are known for their fast transient speed and very good dispersion. The models we propose are closed back type for ease of usage.

The Planar Ribbon is very small and is an open back type, which is very good for line arrays and open baffle applications.

RT-20021 3KHz to 40KHz, 88db.

RT-4001 2KHz to 27KHz, 89db.

RT-5002 3KHz to 30KHz, 95db.

RT-4101 4KHz to 40KHz, 86db.

SOLEN Électronique Inc.
4470 Av. Thibault
St-Hubert, QC J3Y 7T9
Canada
Tel.: 450-656-2759
Fax.: 450-443-4949
Email: solen@solen.ca
http://www.solen.ca