Resistors in Analog Design

Linear Resistor Technologies

- Composition
- Thick Film
- Thin Film or Metal Film
- Metal Foil
- Wire-Wound
- Some Comments about Matched Resistor Networks

Composition Resistors

- The resistive element is a compacted mixture of carbon and ceramic held together in a resin base
  - *Very popular prior to the 1970s, much less popular today*
  - *Still useful in some non-audio applications that require high peak power capability, or super low series inductance*

- Unimpressive performance by today's standards
  - *Tolerances from 20% to 5%*
  - *TC_R is typically 150 to 1000 ppm/C (worse at low values)*
  - *High modulation noise and voltage coefficient compared to other types*

- DO NOT USE in high performance analog designs!
  - *One notable exception is in the design of certain guitar amplifiers where certain forms of distortion are desired*

Thick Film Resistors

- The resistive element is a conductive film applied to the surface of a cylindrical or rectangular substrate
  - *Resistance is determined by film composition and etching pattern*
  - *Very wide variety of sizes and power ratings*

- Very popular for general purpose applications
  - *Tolerances of 2% to 0.1%, usually laser trimmed when <1%*
  - *TC_R is typically 100 to 250 ppm/C*
  - *Modulation noise is high compared to thin film, foil and WW types, but much better than carbon composition*
  - *Voltage coefficient is rarely specified, and varies considerably from brand to brand, and by value…up to 10 ppm/V is not uncommon*

Thin Film (Metal Film) Resistors

- The resistive element is a more stable conductive film (typically Nichrome or Ta-N) that is sputtered onto the surface of a cylindrical or rectangular substrate
  - *Resistance is determined by film thickness and pattern*
  - *Less of a variety of sizes and power ratings versus thick film types*

- Superior performance, but much more expensive
  - *Tolerances from 1% to 0.02% (usually laser trimmed when <1%)*
  - *TC_R is typically 25, 10, 5, or even 2 ppm/C (very recently)*
  - *Excellent (i.e. very low) modulation noise*
  - *Usually much lower voltage coefficient than thick film, but still rarely specified and variable from brand to brand, and by value…typical values are in the range of 0.1 to 1 ppm/V*

Metal Foil Resistors

- The resistive element is a special alloy metal foil that is cemented to an inert substrate
  - *Resistance is determined by the foil characteristics and pattern*
  - *Trimming is accomplished by opening links in a carefully designed foil pattern—vastly more stable than "L" cut trimming*
- The best DC performance, and most expensive of all resistor technologies
  - *Tolerances to 0.001% with TC_R as low as 0.05 ppm/C !*
  - *Extremely low modulation noise and thermal EMF*
  - *Specified voltage coefficient is typically <0.1 ppm/V at DC*
- Beware for high-end audio applications!
  - *Low frequency modulation distortion is much worse than expected*

Wire-Wound (WW) Resistors

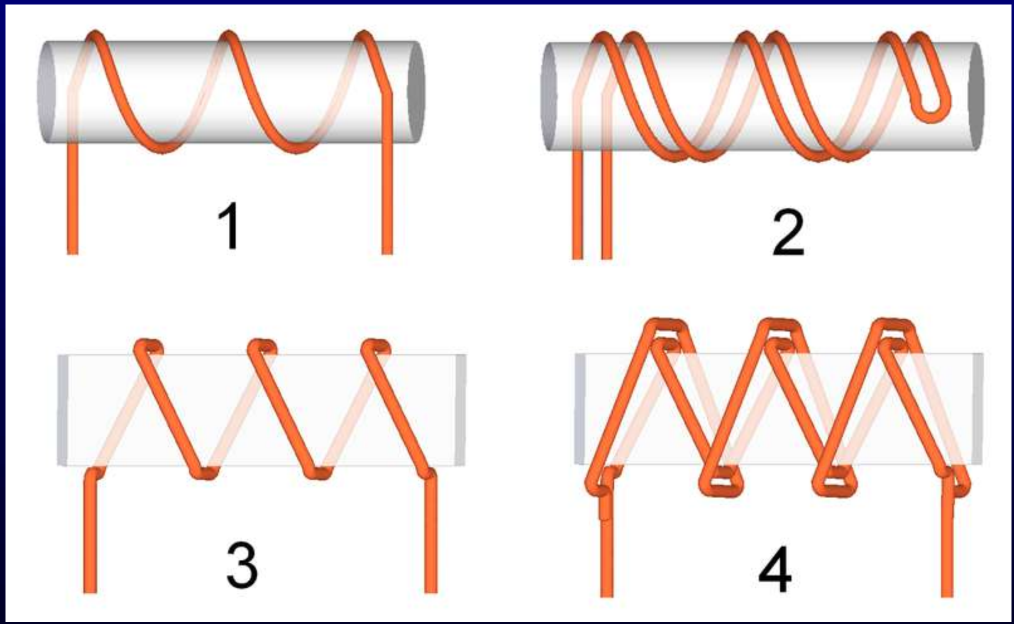
- The resistive element is wire having a low temperature coefficient and carefully wound on a substrate
  - *Typically appropriate only for lower resistance values*
  - *Very high peak and average power ratings are possible*

<u>Winding Patterns</u>

#1 / #3 - Inductive

#2 - Bifilar

#4 - Ayrton-Perry



Resistor Non-Linearity

- Resistors exhibit two general forms of non-linearity
  - *Voltage coefficient and power coefficient ("thermal modulation")*
- Resistor voltage coefficient non-linearity is best modeled as $R(V_s) = R_o * (1 - k_v * |V_s|)$
  - *k_v has units of "ppm/V" and is usually positive*
  - *Taylor series model is not appropriate here!*
- Distortion can be estimated by taking the FFT of a full-wave rectified sine multiplied by the sine
  - *2HD ≈ 0, assuming no significant dc component*
  - *3HD ≈ $|k_v * V_s| / 5.9$ → Note proportionality to V_s not V_s^2 as would be expected using a Taylor series model for non-linearity*
  - *5HD ≈ $|k_v * V_s| / 41$ ≈ 3HD / 7 → 5HD is about -17 dB below 3HD*

Resistor Non-Linearity, cont'd

- Resistor power coefficient non-linearity is similarly modeled as $R(P_s) = R_o * (1 + k_P * P_s)$
  - *k_P has units of ppm/W and can be either positive or negative*

- However, the real non-linearity mechanism is thermal modulation which leads to a much more useful model: $R(V_s) = R_o * (1 + TC_R * Z(\omega) * (V_s\text{^}2 / R_o))$
  - *"TC_R" is the <u>dc</u> temperature coefficient (ppm/C)*
  - *"$Z(\omega)$" is the device thermal impedance (C/W) which is a very complex function of frequency—instantaneous power dissipation changes in a resistor do NOT cause instantaneous changes in the temperature of the resistive material*
  - *As frequency → 0, $|Z(\omega)|$ → θ_R the dc thermal resistance, which is typically 200-300 C/W for a 1206-size surface mount resistor*

Resistor Non-Linearity, cont'd

- At <u>very</u> low frequencies (<0.2 Hz), the resistor reaches thermal equilibrium as the signal varies
  - *2HD ≈ 0, assuming no significant dc bias*
  - *3HD ≈ $TC_R * \theta_R * (V_s \hat{} 2 / R_o) / 4$*
  - *5HD ≈ 0 (compared to 3HD / 7 for voltage coefficient distortion)*
- Within the range of 5-200 Hz the magnitude of Z(ω) is *usually* much smaller than θ_R, rolling off to near zero above 1-5 kHz
  - *Beware: Recent experiments by the author (corroborated by another individual) have shown that some metal foil resistors with exceptionally low TC_R behave as if $|Z(\omega)| >> \theta_R$ at low frequencies, thus contributing higher modulation distortion than a thin film resistor with a larger TC_R*

Recommendations for Audio Circuits

- All factors considered, the best resistor technology for audio applications is a low TC_R thin film
  - *Avoid the common 25 ppm/C characteristic in critical circuit locations, and pay the premium for either 10 ppm/C or 5 ppm/C*
  - *Some manufacturers now offer 2 ppm/C (if you can afford it)*

- For surface mount resistors, use only 1206 size
  - *Smaller sizes have a lower power rating hence a higher thermal resistance which translates to a higher thermal modulation distortion…sizes larger than 1206 are not commonly available*
  - *Limit the signal to 20 mWpk or about 3 Vrms (+12 dBu) for the lowest distortion performance*
  - *Consider using series-parallel combinations in circuits requiring higher peak power dissipation or higher voltage*

Resistor Networks

- Resistor networks are especially useful in applications that benefit from ratio matching
  - *Ratio accuracies can be as good as 0.01% for thin film, or an incredible 0.001% for metal foil*
  - *Extremely low differential temperature coefficients at dc, however watch out for unexpectedly high thermal modulation effects with metal foil types*
- Avoid large R ratios (e.g. 10:1 or higher)
  - *Best performance is achieved if all resistors are of equal value*
- The small size of resistor networks (SOIC-8/-16) will mean a higher thermal impedance, thus causing higher thermal modulation distortion than discrete resistors

A True Story…

- About 13 years ago a certain manufacturer decided to change their network substrate material from ceramic to passivated silicon <u>without</u> notifying its customers
  - *Ceramic is brittle and more expensive to process and cut to size*

- Although the resistor DC parameters were unchanged, the AC performance was a total disaster!
  - *The stray C between each resistor and the substrate was not only higher, but NON-LINEAR*
  - *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 they were about to be disqualified*