Selecting Resistors for Pre-Amp, Amplifier, and Other High-End Audio Applications

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In high-end audio equipment, careful selection of resistors is one of the best ways to avoid or minimize noise and distortion in the signal path. This paper describes the noise generation in resistors manufactured using the various available resistor technologies and quantifies the noise insertion typical for each type.

Noise is an unwanted wide spectrum signal that may be superimposed on any useful signal, including DC. Resistors, like other passive components, are noise sources to various degrees, depending upon resistance value, temperature, applied voltage, and resistor type.

Many experiments have been done to show why some resistors are "noisier" than others. But the only test that audio experts and audiophiles have agreed on is comparing the level of fidelity that results when different resistor technologies are used in actual audio systems.

Noise in resistors

Overall resistor noise has several components. The most relevant for audio applications are thermal noise and current noise.

Thermal noise is notable for being independent of the resistive material. In fact, the thermal noise level is the same for any type of resistor provided the resistances and temperatures are the same. The voltage power spectral density (PSD) of thermal noise S_T [V^2/Hz] is uniformly distributed through the entire range of frequencies. It may be presented by the following expression [1, p.76]:

$$S_T = 4kTR,$$

where
R – resistance of a resistor [Ω],
T – resistor temperature [K],
$k = 1.3807{\times}10^{-23}$ J/K – Boltzmann's constant.

Current noise, on the other hand, has a direct relationship to the type of resistive material. The spectral density of voltage of current noise S_E is found experimentally to be directly proportional to the square of DC voltage drop U across the resistor and inversely proportional to the frequency f [2, p.164]:

$$S_E = \frac{C \cdot U^2}{f}.$$

C is a constant that depends on material of the resistive element and its manufacturing process.

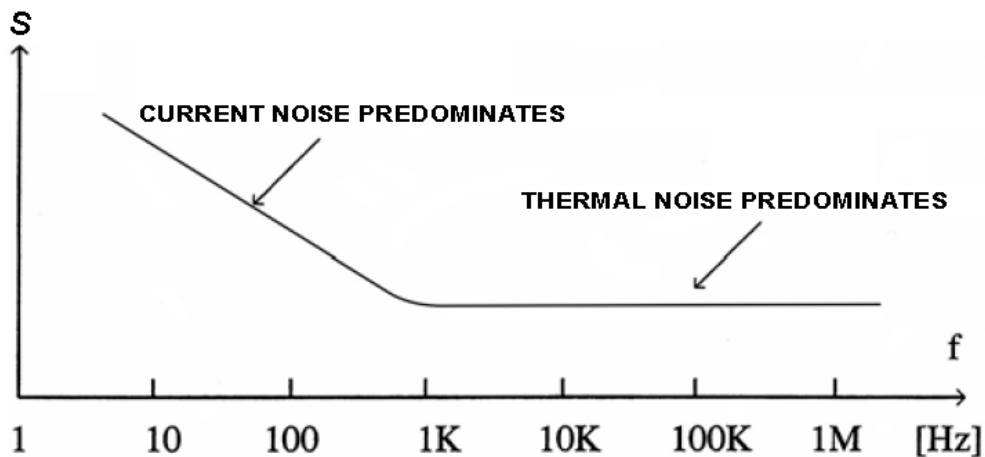The spectral density S of the total noise voltage in the resistor is presented in Fig. 1.

Fig.1: Spectral density of total noise voltage in resistor.

The current noise level in a resistor is commonly expressed in units of µV/V or in decibels (in terms of Noise Index [NI]$_{dB}$)

$$[NI]_{dB} = 20\log\left(\frac{u}{U} \cdot 10^6\right),$$

where u is root mean square noise voltage over a decade bandwidth, and U is the DC voltage drop across the resistor   Both u and U are measured in volts. The lower the Noise Index, the lower the level of current noise in the resistor.

The Noise Index of resistors manufactured using different technologies is presented in the graph below.

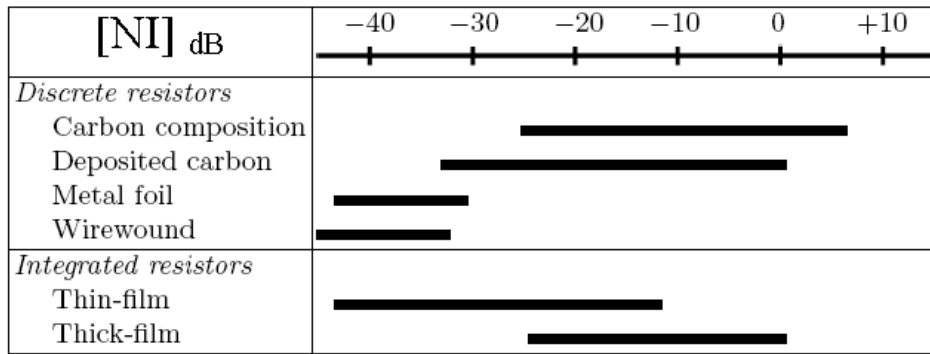| [NI] dB	−40	−30	−20	−10	0	+10
Discrete resistors						
Carbon composition				▬▬▬▬▬▬▬▬		
Deposited carbon			▬▬▬▬▬▬▬▬			
Metal foil	▬▬▬					
Wirewound	▬▬					
Integrated resistors						
Thin-film		▬▬▬▬▬▬▬▬				
Thick-film				▬▬▬▬▬▬		

Fig.2: Average noise indexes of commercial resistors [2, p.168].

As the graph shows, resistors based on composition resistive materials such as carbon and thick film have the highest level of current noise. Why? Because of the significant non-homogeneity of these resistive element materials. The conduction path in composite materials is formed by the conductive particles touching one another in an isolative matrix. Non-stable contacts in these "touching sites" generate noise when electrical current runs across them.

Thin film resistors have a considerably more homogeneous structure and consequently are less noisy. Thin films are deposed using evaporating or sputtering of resistive material (for example tantalum nitride TaN, silicon chromium SiCr, and nickel chromium NiCr) onto a ceramic substrate. The thickness of the layer varies typically from 10 to 500 angstroms depending on the resistance value. The noise in thin films results from the occlusions, surface imperfections, and non-uniform depositions which are more significant when the film is thinner. That is why the thicker the resistive film, the lower the noise level.

The lowest noise level is observed in resistors with bulk metal resistive elements: foil and wirewound. Wire is made of metal alloys similar to foil material, but additional noise may come from the junction of the fine wire of the resistive element and the comparatively coarse resistor terminals. In foil resistors, the terminals and the resistive element are parts of the same piece of the foil, so this problem is avoided. But the major objection to wirewound resistors is their

inductance, which results in chopping the peaks, and the significant dependence of resistor impedance on signal frequency. In addition, special attention must be paid to the following effects associated with reactance of wirewound resistors:

- The audio amplifier may oscillate spontaneously at 5 MHz to over 50 MHz affecting audio quality [3, p.22-6].
- Equivalent series inductance (ESL) can cause large phase shifts affecting audio tone [3, p.22-6].
- The wire coil may act as a pick-up of EMI that may surpass the level of usual current noise [2, p.167].

Foil resistors avoid these problems because they are structured using chemical etching of a flat bulk metal foil so that the current in adjacent current carrying paths runs in opposing directions, cancelling parasitic inductance of these paths. Also, path-to-path capacitances are connected in series, which has the effect of minimizing the parasitic capacitance of the resistor. These low inductance/capacitance resistors are characterized by nonmeasurable peak-to-peak signal distortions.

Bulk Metal Foil resistors are unique in bringing together all of the following features, some of which are very useful for audio applications:

- Low temperature coefficient of resistance (TCR): down to 0.2 ppm/°C (- 55 °C to + 125°C, + 25 °C Ref.)
- Resistance tolerance down to 0.001 % (10 ppm)
- Low reactance, which results in negligible distortion of pulse signals and immunity to circuit self-oscillation
- Load life stability of 0.005 % (50 ppm) at + 70 °C, rated power for 2000 hours or 0.01% for 10000 hours
- Immunity to ESD up to 25,000 V
- Thermal stabilization time < 1 second (nominal value achieved within 10 ppm of steady value)
- Low thermal EMF of 0.1 µV/°C
- Low current noise
- High linearity or low voltage coefficient of resistance (VCR) of 0.1 ppm/V

Bulk Metal Foil Resistors in High-End Audio Applications

High-end analog audio applications require low intrinsic noise, high linearity of amplification, and minimal dynamic distortion. The typical audio amplifier consists of a voltage preamplifier (preamp) and power amplifier (final driver). The voltage preamplifier deals with low-level signals. That is why its intrinsic noise level is critical. Resistors are among the principal noise sources in the amplifiers.

The main requirements for the audio power amplifier are high linearity of amplification and minimal dynamic distortion. Foil resistors are characterized by very low intrinsic non-linearity of the resistive element, which is made from bulk metal. Wirewound resistors and some metal film resistors have similar non-linearity characteristics, but in the real world the intrinsic linearity of the resistors is not sufficient to ensure linearity of amplification.

Audio power amplifiers are often based on a circuit design that is similar to an operational amplifier (Fig. 3). Its gain

$$k = 1 + R2/R1$$

depends on the R2/R1 resistance ratio in the negative feedback voltage divider. The resistors R1 and R2 dissipate power

$$P_1 = \left[V_O/(R1 + R2)\right]^2 R1$$

and

$$P_2 = \left[V_O/(R1 + R2)\right]^2 R2$$

respectively. Therefore

$$P_2/P_1 = R2/R1$$

Commonly k > 2 and consequently R2 > R1. This means that the power dissipation and temperature rise in resistor R2 will always exceed the power dissipation and temperature rise in resistor R1. Even if both resistors have the same TCR (ideal case) the gain of the amplifier will vary because the R2/R1 ratio will depend on output voltage V_O. Thus spikes and pulses that are typical for sound signals may result in transient changes of amplifier gain. The result is a nonlinearity of dependence between input voltage V_I and output voltage V_O (Fig. 4). This phenomenon is called temperature-induced nonlinearity of amplifier [4]. The way to abate it is to choose R1 and R2 resistors having minimal absolute TCR values.
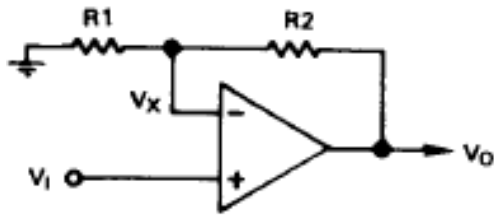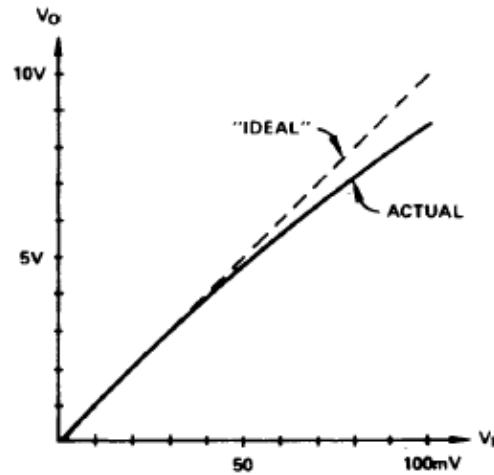
Fig.3: Audio amplifier.

Fig.4: Nonlinear transfer function of audio amplifier [4, p.3].

Resistor parameter that characterizes resistance change resulting from resistor's self-heating is called power coefficient of resistance (PCR).

The PCR behavior of resistors is highly dependent on the type of resistive material. For example, a load of 0.3 W was applied simultaneously to three 1206 size chip resistors manufactured using different technologies:

- Thick-film chip resistor with TCR of about + 42ppm/°C
- Thin-film chip resistor with TCR of about + 4 ppm/°C
- Bulk Metal Foil based on the Z-Foil technology with TCR of about -0.1 ppm/°C.

The results shown in the graph below evidence incomparably smaller resistance change in foil resistor. The stabilized values of relative resistance changes are the following:

- Thick-film chip resistor: +2000 ppm;
- Thin-film chip resistor: -140 ppm;
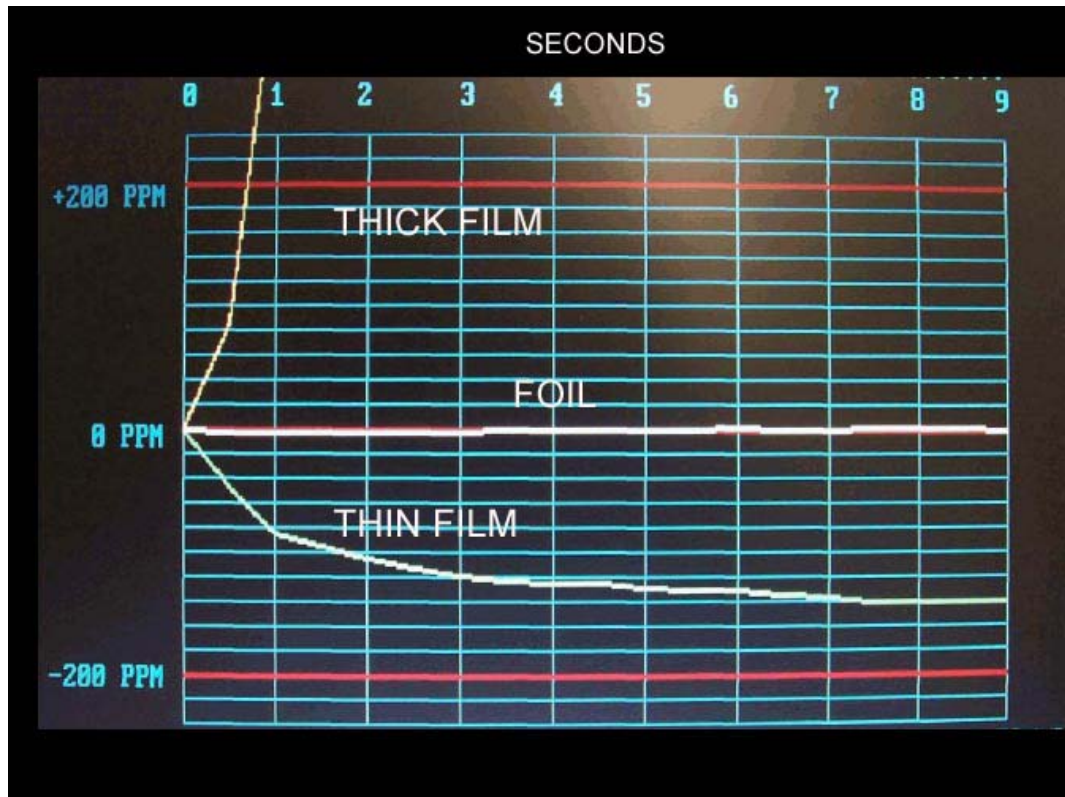- Bulk Metal Z-Foil : + 5 ppm

Fig.5. Self-heating induced resistance changes as functions of time in three types of resistors instantaneously loaded by 0.3W power [5]. Presented time range is 9 seconds.

The Bulk Metal foil resistor is the preferable choice for audio amplifiers when high linearity of amplification and minimal dynamic distortion are required. In particular, Vishay Precision Group recommends the VAR, Z201, S102C, Z203, VSHZ, VSMP Series (0603-2018), VFCP Series, SMRXDZ Series, resistors for noise-free performance in audio applications.
(**www.foilresistors.com**)

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