ASSESSMENT OF NOISE SOURCES IN RESISTORS

Tomáš Kuparowitz

Doctoral Degree Programme (2), FEEC BUT

E-mail: xkupar01@stud.feec.vutbr.cz

Supervised by: Petr Sedlák

E-mail: sedlakp@feec.vutbr.cz

Abstract: Thermal noise and 1/f noise are investigated at room conditions in three kinds of basic off-the-shelf resistors. Samples of carbon film, metal oxide, and cement fixed wire-wound resistors are evaluated. Measurement setup is created to acquire their noise spectral density. Their Noise Index and Hooge's constant are calculated and their useability in low-noise measurement setup is assessed.

Keywords: thermal noise, 1/f noise, noise index, noise spectral density, metal oxide film resistor, carbon film fixed resistor, cement fixed wire-wound resistor

1. INTRODUCTION

Undesired signal fluctuations, also referred to as noise, are common rudimentary processes in all passive and active electronic devices. The understanding of noise turns out to be an important aspect of modern electronics. Because noise level evaluation prove very useful in quality assessment of electronic components [1]. The right choice of such components will positively influence the overall capabilities and class of the device it's used to make. Inversely, the overall noise assessment of electronic device may hint the perks and limitations of such appliance [2].

Understanding and evaluation of several kinds of off-the-shelf resistors is motivation for the remainder of this paper. In the following section this paper introduces elementary noise concepts of resistors. Section 3. Experimental setup describes employed setup for measuring noise of resistors. Resistors attributes and quality are assessed in section 4. Results and discussion. In conclusion to this paper judgment of the experiment and of the resistors tested is presented.

2. NOISE IN RESISTORS

The sources of electronic noise could be divided into two separate groups: *Intrinsic* and *Extrinsic* noise [3].

2.1.   EXTRINSIC NOISE

Extrinsic noise is generated by influences from outside of the measured electronic circuit. Individual components (such as coils, resistors, wires etc.) exhibit this sort of noise because they act as an antenna for external electromagnetic signals. Two main sources of extrinsic noise exist: 1) Useful signals from different circuits or machines, passed in through parasitic coupling. This category has the advantage that it might be deterministic. 2) Environmental perturbations, such as sun winds, etc. Advantage of extrinsic noise is that it might be shielded against. Good instrument design will help to minimize extrinsic noise.

2.2.   INTRINSIC NOISE

Noise induced by circuit's components itself. Every non-ideal electronic element will contribute to the total level of intrinsic noise of the device. These sources of noise have undesirable effects on

the working signal. Two main common attributes of all sources of intrinsic noise are randomness and low amplitude.

Various kinds of intrinsic noise are commonly classified into several types; see [4]. In resistors *thermal noise* and *1/f noise* are prevalent.

Thermal noise is pervasive in all electronic components across the whole frequency spectrum. Its origin is attributed to the random motion of free electrons inside conductive material. The thermal noise is exhibited in a form of white noise, therefore it follows that it's mean value will be zero. For resistors it may however be described in the means of its voltage spectral density

$$S_U(f) = 4kTR \quad [V^2 s] \tag{1}$$

where k is Boltzmann's constant, T the temperature of measured component in kelvins, and R is its resistance. From equation (1) it follows, that the RMS of thermal noise will linearly depend on temperature and resistance of measured resistor.

1/f noise appears at low-frequencies with spectral density that depends inversely on frequency. 1/f noise is commonly found to be present in great range of systems [5]. Such systems encompass electronics, physics, biology and other fields of science.

In electronics this phenomenon hampers the operation of numerous devices and circuits. It may be significant impediment to development of practical applications. Therefore it is useful to expect its effects and to know its ratings for components used. This noise is usually found at frequencies below 100 kHz. [5]

Despite its great influence and length of research in electronics, the physical source of 1/f noise remains uncertain. In resistors it has been experimentally established, that its level changes with voltage applied to the resistor, within measurement bandwidth, given the equation [3]

$$S_U(f) = \frac{CV_{DC}^2}{f} \quad [V^2 s] \tag{2}$$

where V_{DC} is potential applied to the resistor, and C represents Hooge's constant [6] that reflects material and manufacturing process of given resistor. Note that for resistors, made from the same material and using the same technique, the 1/f noise does not depend on its resistance value. The noise then depends solely on voltage applied.

One common merit, used to classify 1/f noise of a resistor, is its Noise Index (NI). It is defined as a ratio of RMS value of the $V_{1/f}$ in μV over the potential applied to the resistor in V, in one decade of frequency [7]. System, fitted by exponential function $V_{1/f}^2 = a.f^{-1}$ would have in single decade

$$\mathrm{NI} = \frac{10^6 V_{1/f}}{V_{DC}} = \frac{10^6 \sqrt{a.\ln 10}}{V_{DC}} \quad \left[\frac{\mu V}{V}\right] \tag{3}$$

Note that the NI is often denoted in dB. Consequently, combining equations (2) and (3), the value of constant C, which depends on NI, can be induced

$$C = \frac{(\mathrm{NI})^2}{\ln 10} = \frac{a}{V_{DC}^2} \tag{4}$$

3. EXPERIMENTAL SETUP

The block diagram of the electrical measuring setup is given in Figure 1. Battery based power source generates potential $U \in 0..12\,\mathrm{V}$ across two resistors, connected in series. R_S serves as bleeder resistor. Measured load resistor R_L is connected by both terminals to low-noise preampli-

fier PA15 (3S Sedlak, Ltd). Measured signal is than routed to an amplifier and selective band filter AM22 (3S Sedlak, Ltd). Intensified signal is propagated via coaxial shielded cable to an analog-digital converter HS3 (TiePie Engineering), which in turn is connected to measuring PC by USB cable. The power source, measured sample, and both amplifiers are shielded from extrinsic sources of noise, using grounded metal box.
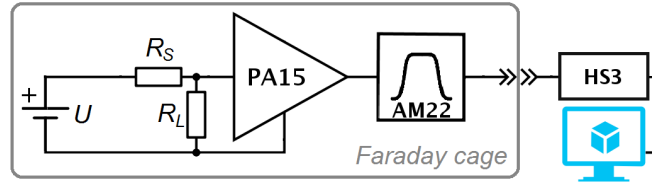

Figure 1: Measurement setup diagram

Measurement is controlled through connected PC, running MATLAB script. Sampling frequency of the AD converter and the limits of the band filter are dynamically adjusted by the program, in order to honor the Nyquist–Shannon sampling theorem. See Tab. 1 for reference of individual measured bandwidths. The measurement software performs FFT for the designated bandwidth, calculating it's noise spectral density. Each measurement is repeated in excess of 20 times per bandwidth and the results are averaged. Invalid measurement sweeps are discarded, following the Chauvenet's criterion, with maximum allowable deviation of 10 samples.

	Band 1	Band 2	Band 3	Band 4	Band 5
Sampling frequency	1 kHz	10 kHz	100 kHz	1 MHz	10 MHz
High-pass filter	0.1 Hz	100 Hz	1 kHz	10 kHz	100 kHz
Low-pass filter	100 Hz	1 kHz	10 kHz	100 kHz	1 MHz

Tab. 1: Measurement bandwidth setup

Three kinds of ordinary off-the-shelf resistors were evaluated for the purpose of this paper: 1) Metal oxide film resistor 10 kΩ. 2) Carbon film fixed resistor 10 kΩ. 3) Cement fixed wire-wound resistor 10 kΩ.

Two specimens of each type of resistor were used to construct three samples. One resistor of the pair was used for R_L and the other for R_S, as shown in the measurement setup diagram. Thus both the R_L and the R_S should have the same properties.

4. RESULTS AND DISCUSSION

Preliminary noise background measurement was performed. During this measurement the input of the preamplifier was shorted. The result is the green curve shown in Figure 2a. Remaining curves in mentioned figure are open-circuit characteristics of each sample. These curves correspond to 0V across R_L (the power source is removed from the measurement circuit altogether).

Resistor noise spectral density measurement was performed with power source step $\Delta U = 3\,\mathrm{V}$ for each resistor pair. This translates to 1.5 V increment across R_L per measurement. Acquired data are plotted in Figure 2b-d. Each graph is reserved for single measurement sample for clarity. Note the difference in y-axis limits of each sample.

Thermal noise spectral density of 10 kΩ resistor (at room temperature) should using equation (1) evaluate to $1.66 \times 10^{-16}\,\mathrm{V}^2 s$. This assumption was met very precisely by carbon film and metal oxide resistors. Wire-wound resistor had slightly lower thermal noise than expected.

By closely examining the measured data plots, little ripples could be observed at regular intervals of some curves. This nonconformity is due to the switching and averaging over different frequency bands during measurement; see Tab. 1. Increasing the number of measurement sweeps would 'iron'

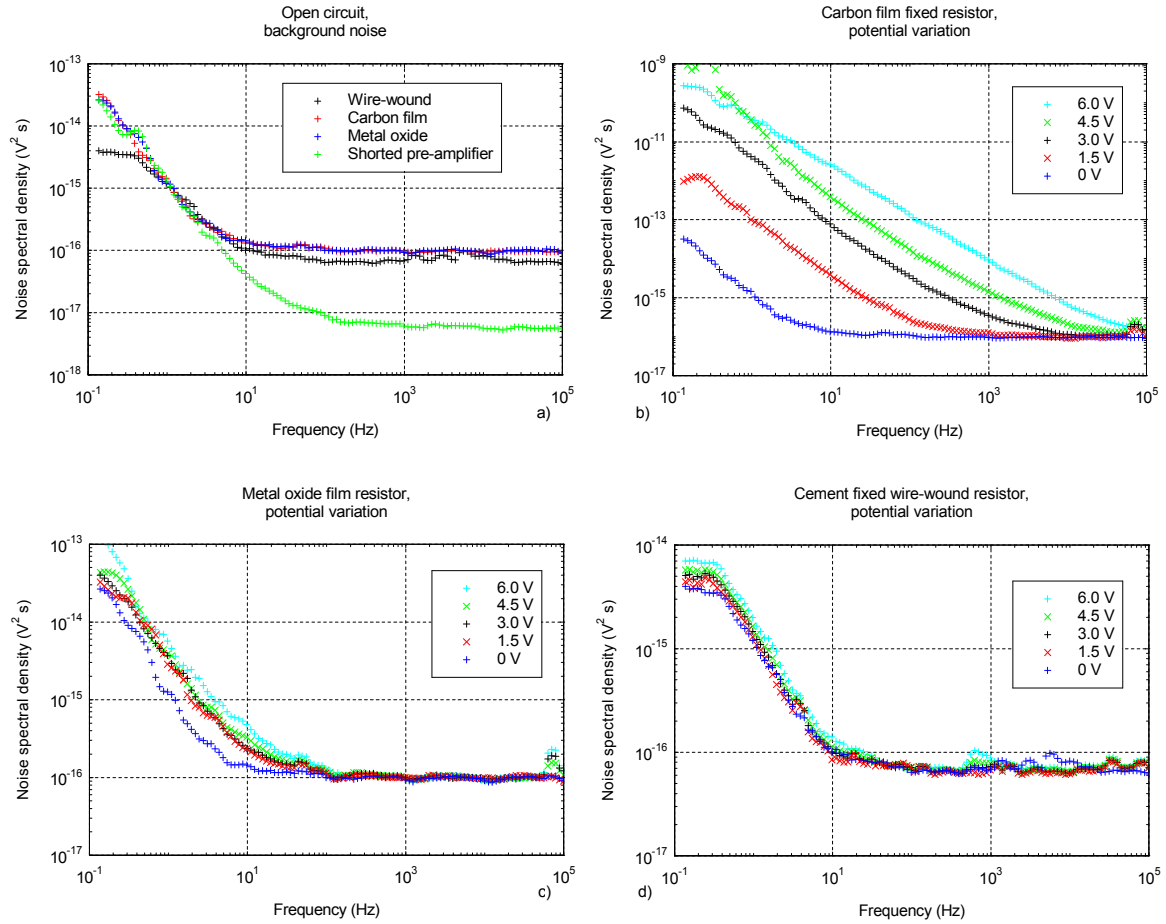down these ripples. This approach is impractical though, because the power source is battery driven.

Figure 2: Measured noise spectral density characteristics; **a)** background noise (shorted preamplifier) and open circuit characteristics of each resistor; **b)** carbon film resistor voltage characteristics; **c)** metal oxide resistor voltage characteristics; **d)** wire-wound resistor voltage characteristics

Vigilant reader might have noticed, that per sample curves in Figure 2a are redundant, since they are repeated in Figure 2b-d (as 0 V). Their placement in Figure 2a serves to delineate the influence background noise of preamplifier has on the measured signal at low-frequencies. The relation of the interference points to diffusion noise as being the likely candidate. The placement and amplitude of background noise is unfortunate (but not lethal) for 1/f noise measurement of 10 kΩ resistors. The reason being that at frequency 10 Hz it collides with thermal noise level of such resistor.

	1.5 V		3.0 V		4.5 V		6.0 V	
	Ni_{dB}	C	Ni_{dB}	C	Ni_{dB}	C	Ni_{dB}	C
Carbon film	-10.81	3.60e-14	-8.71	5.83e-14	-3.65	1.87e-13	-2.26	2.58e-13
Metal oxide	-26.74	9.20e-16	-32,17	2.63e-16	-35.24	1.30e-16	-35.37	1.26e-16
Wire-wound	-30.30	4.05e-16	-35.69	1.17e-16	-38.40	6.28e-17	-40.02	4.32e-17

Tab. 2: Noise Index (NI) and Hooge's quality index (C) calculated for measured resistors per voltage

Assessment of low-frequency noise was hampered by the interference of measuring equipment. In concordance with theory, noise spectral density tends to rise with voltage applied to resistor. Except for carbon film resistor, whose 1/f noise was very significant even in high frequencies, the low-noise relations had to be extracted by fitting from very noisy signal. Using (3) and (4), the NI

and C were calculated from coefficient a of the fitted curve and are shown in Tab. 2. Comparison of common industry values of NI could be found here [3]. Note that NI should be constant with varying voltage applied to resistor. Not being so is likely due to fallible measurement setup. While NI of carbon film resistor increases with applied voltage (the resistor gets noisier), NI of metal oxide and wire-wound resistors decrease with the factor of 100 times with growing potential. This behavior is likely caused by the discussed background noise.

5. CONCLUSION

Noise measurement setup was created. Noise of 10 kΩ off-the-shelf carbon film, metal oxide, and wire-wound resistor was assessed. Thermal noise values were in concordance with literature. 1/f noise deduction was aggravated by the equipment setup noise, but satisfactory values were reached by fitting. Overall values of NI are in agreement with the literature (for standard commercial components). Overall findings were satisfactory. Wire-wound resistor even proved to be less noisy than expected.

Both wire-wound and metal oxide resistors proved to be good candidates to be used in low-noise applications. It is to be noted though, that the best effort went into shielding the measurement setup from extrinsic sources of noise. Wire-wound resistor might be highly susceptible to equivalent series inductance in real setup and could act as an antennae to pick-up parasitic signals.

Problems with the measurement background noise could be tackled in the future. In particular two methods reportedly exist to limit the interference: 1) 0°/90° subtraction method [7], and 2) 45° cross correlation technique [8]. Their use would however imply re-factoring of the measurement setup.

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