Audio Engineering Society

Convention e-Brief 486

Presented at the 145th Convention
2018 October 17 – 20, New York, NY, USA

Measuring and Evaluating Excess Noise in Resistors

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ABSTRACT

All resistors generate white (Johnson-Nysquist) noise based on their value and temperature; they can also generate several other types of (excess) noise. The amount or characteristics of a resistor's excess noise could be one factor contributing to variations in perceived sound quality. This research explores methods for measuring the Johnson-Nysquist and excess noise of different resistors with the hopes of quantifying the performance of the components under test. A methodology is proposed for evaluating the audibility of both Johnson-Nysquist and excess noise that requires no special measurement equipment, only a sound system with suitable computer and freely available software.

1 INTRODUCTION

Resistors can be constructed from a variety of materials, including bulk carbon, thick film, thin film, wirewound, and metal foil. The benefits of each material are not clearly documented. Resistors are known to generate multiple types of internal noise and this research examines if variations in internal noise could account for audible differences in resistor performance.

The most prominent is a form white noise referred to as *Thermal* or *Johnson-Nyquist* noise (hereafter referred to as *Johnson noise*). The amount of this *Johnson noise* is a function of the resistance value and the device's temperature.

Beyond this *Johnson noise*, two types *excess noise* (sometimes referred to in other texts as *current noise*) were initially considered relevant by this research: $1/f$ or *flicker noise* [1], and *shot noise* [2]. In many practical applications these types of *excess noise* are masked by the *Johnson noise*, but they are worthy of consideration in the carefully designed low-noise circuits built for audio applications. In the data collected throughout this research *shot noise* was not observed, so this report focuses primarily on quantifying and analyzing *excess noise* as *flicker* or $1/f$ noise.

Excess noise can consist of multiple sources that follow a $1/f^{\alpha}$ spectrum and is only present when current is flowing through the device.

Current is a function of the applied voltage and the resistance, and most types of *excess noise* are functions of both resistance and current, the two resistance terms cancel and the *excess noise* RMS value is only linearly dependent on the applied voltage for a given resistor type of construction. Construction will have a dependency on value so it is not correct to say the noise is independent of value alone [3], [1].

Flicker noise follows the $1/f^{\alpha}$ spectrum where $\alpha \approx 1$.

This is the same spectrum as pink noise, with equal energy per octave. Equivalently this can be stated as power per unit bandwidth drops 3 dB per octave. We will use the term $1/f$ noise throughout the remainder of this paper to mean *flicker* noise.

Graphically we can illustrate the $1/f$ and *Johnson* noise in a plot like the example shown in Figure 1 where $log(spectral - density)$ is plotted versus $log(frequency)$.

The discussion of resistors in audio circuits often centers around achieving the least amount of noise within the audible spectrum. While careful circuit design can help mitigate *Johnson noise*, changes in the resistor materials or construction will not have an impact on the amount of *Johnson noise* [4].

Excess noise could be affected by materials, component design, and variations between construction methods[5]. Different manufacturers of resistors could yield variations in the amount and coloration of *excess noise*, and thus a potential impact on the perceived sound quality.

This research examines methods of testing and quantifying *excess noise* that consists only of *flicker noise* as the source of $1/f$ noise, and offers suggestions for aural comparison methods that could facilitate subjective evaluation of the noise components to determine which resistor might best suit a particular circuit designer's preferences.

Acknowledging that noise is not the only possible difference in resistor performance, the research had originally intended to also measure variations in total harmonic distortion (THD) between resistor materials. As most measurements for THD are actually THD+N, understanding contribution from N (the noise) is important. For example, in semiconductor devices available today, the THD contribution may be lower than the noise contribution. Based on the complexity of the noise topic alone and challenges encountered throughout the data collection process, it was decided that investigation of THD in resistors would need to be conducted separately.

Building off of this work towards developing a testing methodology and framework, further study into *excess noise* on a wider range of resistors as well as THD could be undertaken. In the future similar investigations could be conducted across other passive components found in the audio path, like capacitors.

Setting some of these other variables aside allowed this study to focus on:

1. Developing a system and methodology for testing multiple resistors consistently and repeatedly.
2. Quantifying *excess noise* across various resistors as carefully as possible with the test equipment available.
3. Recommending simple ways to compare resistor noise audibly without specialized test equipment.

2 BACKGROUND

Johnson noise can expressed with equation (1) or (2) where T equals temperature in kelvin, R is the resistor's value in ohms, and k_b represents Boltzmann's constant in joules over kelvin. Equation (1), in which v^2 is the power spectral density of the noise in volts^2 per hertz, does not incorporate a variable for frequency as the system is considered ideal. However, real systems will always have finite bandwidth.

$$v^2 = k_B T R \tag{1}$$

In equation (2) the results are expressed as RMS (Root Mean Square) voltage. This is more appropriate for evaluating audio circuits where inclusion of bandwidth represents the range of human hearing (20 Hz - 20 kHz).

$$E_{RMS} = \sqrt{4 k_B T R \Delta f} \tag{2}$$

As is evident in both equations, an increase in the value of the resistor or an increase in the operating temperature will yield an increase in the RMS noise. Circuit designers carefully consider resistor values, thermal conditions, and board layouts to keep operating temperatures low and minimize *Johnson noise*.

The noise calculated by equations (1) or (2) are based on fundamental laws of physics; a measurement of the noise in excess of the amount that a perfect part creates is the more meaningful unit of measure in determining the resistor's quality. *Excess noise* is defined as:

$$E^2_{Excess} = E^2_{Total} - E^2_{Johnson} \tag{3}$$

Where E represents the RMS noise voltages within the defined measurement bandwidth and $E_{Johnson}$ is the value calculated in equation (2). The $1/f$ and *Johnson*

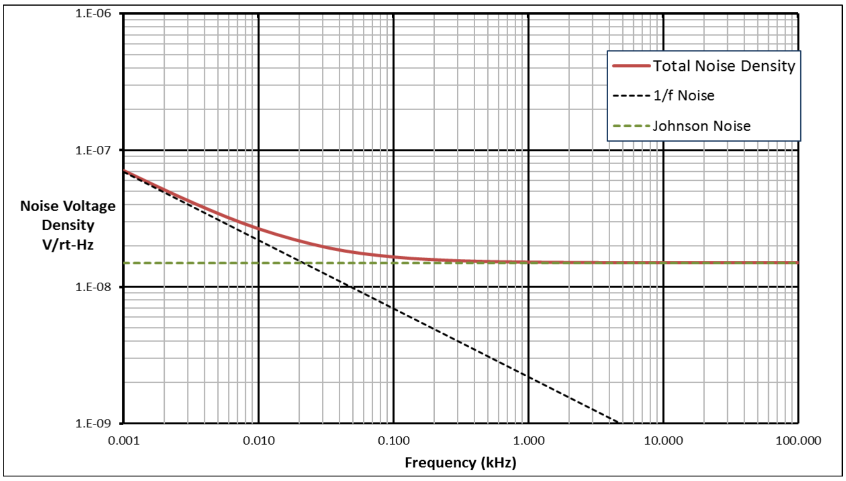

Fig. 1: Generic $1/f$ (pink) noise, *Johnson* (white) noise, and their RMS sum amplitude spectral density versus frequency plot. The *knee* is the frequency where the two lines cross.

noise are uncorrelated with Gaussian probability distributions and therefore add as the sum of the squares for computing RMS values.

The level of *excess noise*, which is dominated by $1/f$ noise in the resistors considered, can be described by a dimensionless value called the noise index (NI). It is calculated using the equation (4), where $E_{RMS_{dec}}$ is total *excess noise* voltage in a decade in uV (micro volts) RMS, and V_{DC} is the applied DC voltage in volts:

$$NI = 20\log_{10}\left(\frac{E_{RMS_{dec}}}{V_{DC}}\right) \quad (4)$$

The NI value is expressed in dB where 1 uV RMS of noise in a decade with 1V applied would correspond to a NI value of 0 dB. $E_{RMS_{dec}}$ is determined by measurement.

For a part with the *excess noise* only from $1/f$ noise we can use any convenient decade of frequency range to calculate $E_{RMS_{dec}}$. Knowing the only non-Johnson noise contribution is the $1/f$ noise then the slope of the line from the $1/f$ contribution is known, and we only need one data point from a measurement to compute the NI. This value should be taken from the left side of the curve of Figure 1 and not near the knee in the curve where the *Johnson noise* starts to dominate the sum. To summarize the assumptions:

- Resistor noise consists of only *Johnson* and $1/f^{\alpha}$ noise where α is 1.
- The amplitude spectral density data extends low enough in frequency to obtain a data point where the $1/f$ noise amplitude is at least 5 times the *Johnson noise*, or for the $1/f$ noise curve (line on a log-log plot) to be inferred.

Typical noise index (NI) values of common resistor constructions are shown in figure 2, which is adapted from information provided in writings by resources from Texas Instruments [6], Resistorguide.com [5], Riedon [7], and Vishay [8], although they do not all seem to be in agreement with each other on the range of NI values a particular technology can offer.

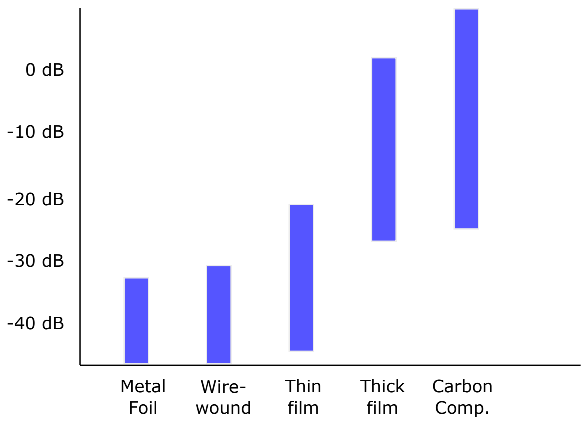

Fig. 2: NI typical ranges for resistor technology type

The IEC 60195:201X standard [9] and the US Military MIL-STD-202-308 [10] define specific measurement conditions by defining a specific analog filter followed by a RMS measurement to allow direct comparison of different parts' $1/f$ noise. Any type of noise other than *Johnson* increases the NI, but only if that noise happens to fall in the same bandwidth as the standard defined analog filter is in.

When equation (4) is rearranged to provide the RMS excess noise value for a part with a given NI and the part has no DC voltage across it then the excess noise is for all practical purposes zero. In contrast *Johnson noise* is neither a function of the voltage nor the current applied to a resistor.

E^2_{Excess} and $E^2_{Johnson}$ can be directly determined from a plot like that of Figure 1, which in turn can be measured directly by a test fixture like that described in Appendix B where the measurement device provides an appropriate FFT output as detailed in Appendix A. For *Johnson noise* equation (2) is used; the theoretical value from equation (1) should match the value determined from the plot, though as will be shown in the example of Figure 4 it is possible that the excess noise dominates the *Johnson noise* across the audio spectrum.

2.1 Interpreting $1/f$ noise audibility

The use of weighting (filtering) for noise measurement is based on two generally accepted facts about noise in electronic equipment. 1) the level of noise is generally low relative to the signal level. 2) human hearing is non linear in sensitivity with respect to both frequency and level. The common *A*-weighting curve is approximately the same as the Fletcher-Munson like sensitivity to low level (40 phon) sounds.

A weighting is considered a reasonable way to estimate the audibility of low levels of noise for a system used for recording or playback of typical audio; music, speech, theatrical releases, etc. Understanding the use of weighted measurements is important in understanding the audibility of $1/f$ noise as *A* weighting at low frequencies is roughly the inverse of the $1/f$ spectral density curve.

2.2 Use of results based on FFT

There are a number of considerations when using FFTs to determine the total noise power. For the reader that is unfamiliar with FFT techniques with broadband signals please see Appendix A.

Compared to the analog measurement techniques for excess noise of the IEC and MIL standards, the FFT method provides considerably more insight in to the nature of the noise. It also offers opportunities to make experimental errors that the analog technique may not suffer from.

In the experiments performed here, the unexpectedly noisy 2.5 kΩ wirewound parts served as a known reference for every data collection run. This meant results that appeared incorrect could mostly be validated by looking at the reference channel result. If a reference channel was not included as part of the test then the test setup has to be changed between measurement and calibration, leading to increased risk of error in the execution of the measurements.

3 EXISTING RESEARCH

Resistor manufacturers do not publish the NI values for their parts; at best one finds vague marketing statements. However one resistor manufacturer did share results with the authors of their measurements made as part of their development of special thin film resistors with a very small amounts of $1/f$ noise [11].

There is a large amount of information about *Johnson noise* in textbooks on electronic circuit design [12] as well as research on $1/f$ noise in semiconductor devices [13]. While there are some older papers on noise measurement [14], few articles detail $1/f$ noise in resistors used for audio. Even the terms *excess noise* and *Noise Index* are not found in the on-line AES dictionary [15].

For the audibility of $1/f$ noise there is a body of work related to environmental noise in buildings and facilities for critical listening, but the spectral and time domain nature of those noise sources is not the same as that associated with $1/f$ noise and therefor the authors do not think those studies can aid in an audibility criteria for $1/f$ noise.

One may also attempt to infer an upper limit for audibility of $1/f$ noise from other research. For example research conducted evaluating noise shaping of quantization error [16], [17] suggests that low levels of low frequency noise is attenuated in the hearing process, though with noise shaping research the testing for audibility is focused at higher frequencies.

A definitive qualitative study for audibility of $1/f$ noise does not seem to have been published yet; this kind of research could help determine what level of $1/f$ noise would be audible for discerning listeners in a typical critical listening environment. Conclusions from this sort of study could offer an absolute psychoacoustically determined limit of audibility that could serve as a design goal for equipment designers.

The 1981 AES paper by Louis Fielder [17] *Dynamic Range Requirement for Subjective Noise Free Reproduction of Music* states: *"A dynamic range of 118 dB is determined necessary for subjective noise-free reproduction of music in a dithered digital audio recorder."* From Fielder's [17] determination, one can argue that a dynamic range (DR) of 118 dB would be a very conservative value for $1/f$ noise as Fielder looked at the ear's most sensitive frequencies, and $1/f$ noise for low NI parts happens at the ear's least sensitive frequencies, i.e. less than 100 Hz.

Another Fielder paper from 2017 addresses the audibility of distortion and again low frequency components are not heard until higher levels [18]. Some papers look at noise audibility as part of its masking effect [19], [20]. With no specific studies of $1/f$ noise audibility the authors feel these somewhat related studies provide a reasonable starting assumption about audibility of $1/f$ noise; our hope is some future researcher could provide definitive data that would help aid the design criteria.

For $1/f$ noise non-audibility, the human ear's limited response to low frequencies is also aided by consumer playback system have rapidly rolloff below 30 Hz. In the authors' opinion from years in the consumer playback environment $1/f$ noise below 10 Hz will not be reproduced in any conventional playback system. These lower frequency audibility and reproduction limits suggest that parts with low NI, i.e. where the knee between the white (*Johnson*) and pink ($1/f$) noise is below 100 Hz, will have no audible difference in a system.

For electrical circuit design of a typical consumer audio system with a 0 dBV (1V RMS) full scale output, the noise for 118 dB DR would be 1.3 uV RMS. Based on Lipshitz et al modified E-curve weighting [16], if we take a middle of the road number for noise audibility outside of the most sensitive frequencies, an increase in 10 dB over the white noise floor is acceptable. In our example this would be about 4 uV RMS measured in a 10Hz to 100 Hz bandwidth, which for low NI resistors is not a problem.

4 TESTING METHODOLOGY

The two common standards for resistor noise measurement, IEC60195 [9] and MIL-STD-202-30 [10], specify use of an analog filter centered on 1 kHz with -3 dB points of 618Hz and 1618Hz. The measured noise voltage in that frequency band includes all sources of noise. For modern low excess noise resistors the Johnson noise can easily dominate. Also the single RMS voltage measurement of the filter output does not provide any insight in to the spectral nature of the excess noise. Is it just $1/f$ plus *Johnson* noise or are there other components present in the measured RMS value? The IEC and MIL test methodology can not answer that.

For this study, the researchers chose to follow the test procedure developed by Frank Seifert [21], with some variations as outlined in the work of Peter Märki [22].

Seifert's two novel methods relative to the testing standards were to use a FFT to directly plot the noise of the system, which allows a direct measurement on the noise power in any frequency band, and to use a bridge configuration of 4 DUT (Device Under Test) resistors to reduce common mode noise that could exist in the IEC and MIL test methodologies if not performed under very carefully controlled conditions.

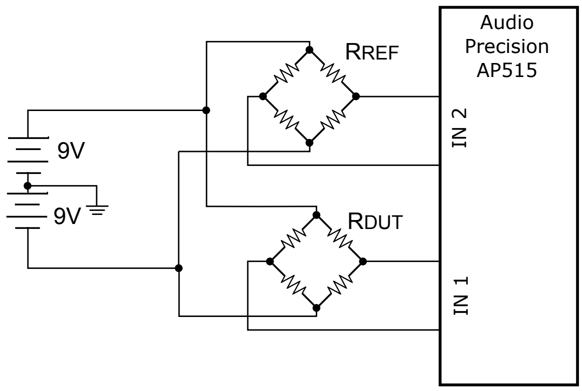

Fig. 3: Test system architecture

Seifert shows that in a bridge configuration the measured noise from the bridge of four resistors with value R and an applied voltage V_x is the same as that of a single resistor of value R with an applied volatge V_x [21]. By using the FFT results, we could pick a frequency decade where the $1/f$ noise was significantly larger than the Johnson noise while at the same time ensuring that there were no test fixture or instrumentation artifacts of concern. While the NI value calculated in this manner should yield the same NI value as calculated via the IEC and MIL test standards, there is no way to verify that without precisely replicating the measurement following each of their methodologies. The cost and time needed for such verification were beyond the scope of this research.

More importantly, the question(s) to be answered were if one type of resistor had measurably better NI than another type; relative differences in NI should be insensitive to exact methodology used.

The excellent results of Siefert's work suggested that this approach of relative NI measurements could work well. For data reduction the spreadsheet developed by Bruce Trump [23] was used with a small modification to directly take the AP515's plot results and calculate a NI value.

5 TEST DESIGN AND FIXTURE BUILD

The work for this was an unfunded project of the Audio Builders Workshop (ABW, part of the Boston section of the AES) with a goal of making it easy for others to continue the work with minimal expense. A low cost fixture was designed and constructed in a cookie tin for noise isolation. Audio Precision was kind enough to make an AP515 available for performing the measurements, and its input noise specification are low enough that we expected to be able to make useful measurements without need of an additional LNA (low noise amplifier).

Details of the fixture are described in Appendix B.

In addition to the physical fixture, SPICE based simulations were performed to compare a model of a theoretically perfect $1/f$ + *white* noise generative resistor with a DC bias applied to actual measurement results. The simulations were created across different bandwidths to validate that the physical measurement and the theoretical value from SPICE were in agreement.

Standard SPICE resistor models do not include $1/f$ noise and therefore a macro model that includes a perfect (*Johnson noise* only) resistor plus a $1/f$ noise model was used.

A detailed example of the data capture and analysis can be found in Appendix C.

6 CHALLENGES

While the Audio Precision AP 515 has a well specified input noise performance of <1.4 uV RMS (20 kHz BW) its $1/f$ noise is not specified [24]. NI values below -40 dB are typical in these measurement, which in this experiment with a bias voltage of 18 VDC creates a noise level close to the inherent noise floor of the AP.

Measurements with the AP515 input shorted showed that using the input with AC coupling feature enabled approximately doubled the AP515's internal $1/f$ noise, so measurements were performed with DC coupling instead. However, DC coupling does increase the value of the 0 Hz FFT bin which is spread in frequency by finite sequence length. The impact of that was removed by using a 128K point FFT (to create small bins sizes) and ignoring frequencies below 5 Hz. The AP's default equiripple window, which is a modified Dolph-Chebyshev design, has a side lobe level of -147 dB and the small DC value would make this term have negligible impact on the measured noise curve.

A newer AP555 was compared to the AP515 for $1/f$ noise. Though the AP555 has lower overall noise its $1/f$ noise is higher; if we treat it like a resistor this the same as saying the AP555 has a worse (higher value) NI than the AP515. The difference in equivalent NI is small, about 2 dB.

Wirewound resistors were chosen as an ideal [25] (i.e. *Johnson noise* only) resistor to determine the test system noise as they are known to have one of the lowest NI values among resistor types. Only metal foil resistors have a lower typical NI, but they are very expensive and were not feasible with available experimental resources. Several different values of wirewound resistors were measured and their $1/f$ noise was at the limit of the test setup, with one notable exception discussed in Appendix C. A small amount of experimental error was encountered because the ambient temperature for the test fixture was not constant, which resulted in different levels of *Johnson noise*. The estimated temperature range (± 3°C) induced error was small relative to the effects being measured and for all but the lowest NI parts.

7 AUDIBILITY TESTS

The question of "does $1/f$ noise matter" became more crucial in trying to draw conclusions about a particular part's impact on sound quality. As data was accumulated, it was observed that what are often commonly considered 'inferior' resistors [7] actually had small NI values. In addition to the research surrounding subjective perceptions of noise that is reviewed in Section 2 of this paper, an informal test was developed that can be replicated using freely available software (like Audacity) and the listener's preferred headphones or reproduction system.

An upper bound on the maximum allowable noise level could be made based on the same criteria used for white noise [4] but the variation in spectra associated with $1/f$ noise and the ear's lower sensitivity could make previously defined white noise criteria overly conservative.

To provide an initial sense of important characteristics for audibility of $1/f$ noise, Audacity was used to create white noise and pink noise, and then mixed to create a noise profile that would simulate that generated from a specific resistor value with a specific NI.

By changing the pink noise level, the knee in the response curve is being adjusted from the linear (when plotted log-log) $1/f$ curve to the flat white noise portion.

Figure 4 shows a typical plot of the created noise. The rolloff below 5 Hz appears to be a built in high pass filter in Audacity. This will not audibly affect any results as this is outside of the commonly understood range of human hearing, and beyond audio reproduction capabilities. The composite noise signal was then mixed at different levels with short passages of different classical and rock music and a determination was made by the authors as to when noise became audible during playback.

All source material levels were normalized to the absolute peak level in each segment to represent 0 dBFS. Audacity's feature for calculating RMS program level was used to set the level of the composite noise signal for the desired amount; tests were done ranging from -40 to -80 dB below the Audacity calculated RMS program level, which in turn was -15 dB to -25 dB below the peak in the selected passage. The audibility of the

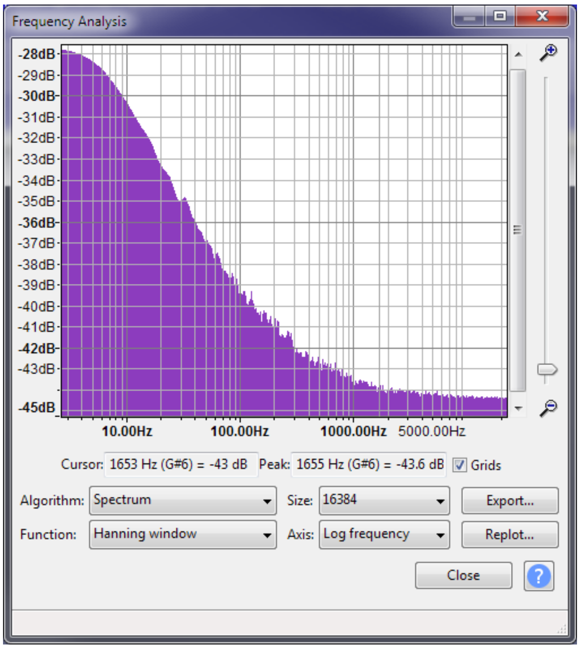

Fig. 4: Pink noise and white noise created and added in Audacity

noise alone was also observed. Samples of the simulated noise are available from the author's website [26], along with recordings of actual resistors [27].

Using the results of the listening tests provides a value for the maximum noise level that would be audible. Two different numbers actually result; one for level relative to the peak value - which is best thought of as the 0 dBFS (clipping) level of the system, and the other a value relative to the average content level, which may be more useful in analyzing how it will sound on a real system.

The EIN (Equivalent Input Noise) of the device (most likely an amplifier) can then be computed relative to the signal level. The source or amplifier impedance, along with the temperature, will determine the *Johnson* noise level [28]. As described in section 1, $1/f$ noise is (for all practical purposes) a fixed level that is neither affected by source impedance nor operating temperature.

Line level inputs connected to low-impedance sources are not going to have *Johnson noise* as the primary noise source. Low-level inputs such as microphones will be much closer to the *Johnson noise* levels and the amount of *Johnson noise* in typical operating conditions must be considered in the design process.

Ideally, this subjective portion of the research would be extended to a more formal test that could help provide a meaningful determination on what a population of critical listeners might be able to discern. Financial and logistical issues prevented the authors from performing this critical aspect of determining a meaningful acceptable value for $1/f$ noise level.

8 OBSERVATIONS

Only a small selection of resistors were able to be tested during the period that the (loaned) test equipment was available. A plan to evaluate results and conduct a second, larger set of tests can hopefully be realized in the future to provide a database of NI values for audio electronics designers for typical brands of resistors. Alternatively, resistor manufacturers could include NI values in their data sheets, perhaps derived through a standardized methodology that overcomes the possible test issues based on IEC or MIL methods, along with other potentially valuable measurements including THD.

The author's test setup was limited by the AP515 input noise and can be taken to be equivalent to a NI in the -45 to -48 dB range for the fixture used. These measurements are flagged with an asterisk in the results.

Table 1: Wirewound resistors, Ohmite WN series

Resistance	NI	Notes
1K	-43 dB	
2.5K	-36 dB	ref resistor
5K, 10K	-48 dB*	measurement limit

Table 2: Carbon comp resistors, unknown manufacturers

Resistance	NI	Notes
2.2K	-40 dB	
22K	-18 dB	

The low NI value for the 2.2K part is not characteristic of carbon comp resistors, raising a question if perhaps the supplied parts were actually a different technology.

Table 3: Film resistors

Resistance	Manuf-Series	NI	Notes
10K	Panasonic-ERA	-48 dB*	test limit
2.2K	Susumu-RS	-48 dB*	test limit
1K	Susumu-RG	-45 dB*	test limit
10K	Susumu-RG	-45 dB*	test limit
10K	Susumu-RR	-40 dB	
2K	Stackpole-axial	-44 dB*	test limit
2K	Yagoe-Thick film	-17 dB	

8.1 Guidance for further measurements

The limited data set does provide some indication for what a more complete study could entail:

- Compare through-hole versus surface mount components for a given power rating.
- Compare different power ratings.
- Compare a wider range of resistance values to determine if material properties and/or construction techniques change in certain resistance ranges.
- Examine a statistically useful number of the same resistive element technology in the same power/value between different manufacturers.

Even if the above steps were performed the database created could never cover all possible parts a designer may wish to use, and manufacturers introduce new parts on a regular basis. The best approach for critical applications is to measure the NI of the planned parts and any approved crosses to determine their suitability.

9 CONCLUSION

While the general rules regarding resistor noise expressed in Figure 2 were observed for different construction methods (carbon having the nighest noise index, and wirewounds being close to noise-free) there were some unexpected results. For example, the 2K ohm wirewound parts were very noisy, while all other wirewounds were close to ideal.

Specialty low (excess) noise thin film resistors yielded NI values at the same low level as the measurement system noise floor as generic thin film parts. While an improved test fixture would no doubt provide data to make a clear judgment of which has the lowest NI, the authors believe that both part's low NI would mean no audible difference in any reasonable circuit application.

Initial research into $1/f$ noise audibility didn't provide conclusive results for a best methodology to determine absolute audibility criteria. By allowing some generous assumptions about very quiet listening environments and the audibility of $1/f$ noise, it could be concluded that for resistors in an audio signal path with a typical DC bias applied as found in semiconductor circuits, components with a NI value less than -30dB would provide sufficient design margin.

Tube design with voltages of hundreds of volts results in significantly higher excess noise from equation (4) than semiconductor circuits; the tubes themselves also contribute to the problem [29].

9.1 Suggestions for improvements and future research

The hand built test fixture provided reasonable performance, but the residual $1/f$ noise of the AP515 did not allow direct measurement of the lowest NI parts. An improved fixture built on a PCB and with a low noise differential amplifier(s), as recommended by Seifert [21], could provide more accurate measurements of very low noise parts. Using additional gain stages to allow use of a PC soundcard for acquiring data may be problematic as most soundcards are not DC coupled, and are often inherently uncalibrated.

Metal foil resistors were not tested as they are relatively expensive (over 20 times the cost of even the most expensive thin film resistors tested). Without a research budget they had to be omitted, but should be considered in the future.

Audibility of pink-plus-white noise under different listening conditions remains under-researched. To determine what NI level a system designer should target, a separate study under controlled conditions should be conducted beyond the simple *'try this at home'* experiment described here.

This research focused on measuring only the resistor's NI, not on the total $1/f$ noise in typical application circuits. A part with a high NI value may be acceptable if used in a circuit where the DC voltage applied across it is small.

Also not considered in this research is the instantaneous $1/f$ noise that can be caused by a large AC voltage applied across the circuit. A quick analysis suggested that the same body of work for using AC excitation of sensors and/or chopper-stabilized amplifiers may apply. The result would likely be that the $1/f$ noise, for all practical purposes, disappears in to the system (white) noise floor. A rigorous analysis and measurement confirmation is needed before any conclusion can be made.

10 ACKNOWLEDGMENT

The authors would like to thank the members of the Boston section of the AES that provided encouragement, review and feedback on this work. Audio Precision's extended loan of an AP515 was also critical to making the measurements and their support is acknowledged. Lastly, we thank Dr. Kuma Takamura and the staff at Susumu USA for sharing internal research results, parts samples, as well as their booth at the 2017 AES convention, which served as the original inspiration for this research.

A Use of FFT for determining NI

Based on the amount of improperly documented results seen in datasheets and trade literature, it's worth mentioning some fundamental points regarding FFT interpretation. The first is that broadband signals, like white or pink noise, can not have their (total) RMS level determined from the FFT plot without knowing the FFT size and the window function applied. Many plots are just concerned with the relative level of two pure tones (for example like the fundamental and the 3rd harmonic) and this other information isn't needed to make a determination of relative levels.

For the reader that is new to FFT based measurements we offer this quick example to illustrate the issues with interpreting FFT results with broadband signals such as white or pink noise.

We'll use a 0 to 20 kHz bandwidth for illustrative purposes, the extra contribution from including 0 to 20 Hz is small and is generally ignored when calculating the $\Delta f = f_2 - f_1$.

First, measure the noise power x^2 over a Δf of 20 kHz; then feed that input into two filters with ideal passbands of 0-10kHz and 10kHz-20kHz. Each filter's output would measure $x^2/\sqrt{2}$ as the total RMS power must remain the same, e.g. $P_{Total}^2 = P_{0-10kHz}^2 + P_{10-20kHz}^2$. If divided in to 4 bands then each band would measure $x^2/\sqrt{4}$. Extending this to the case of a N point FFT we can see that the level in the bin is related to the total RMS noise by a$\sqrt{N}$ term if the noise is white.

If the noise power is constant in frequency then the FFT result can be used to determine the total noise power in a bandwidth of Δf. If the noise power is not constant in frequency then the noise must be integrated over the range f_1 to f_2.

Performing a N point FFT on a sequence of data produces large side lobes for a single input sine wave unless the input frequency happens to have an integer number of cycles in the N input samples. To reduce the side lobes window functions are applied to the data, for the reader new to this topic we suggest review of an introductory text on the topic. Window functions can be scaled to have the result of multiplying the windows function by the N input samples have the same RMS power. However many systems use window functions that have a maximum value of unity which means the RMS output power is less then input RMS power. This is done on the assumption that the user will correct for this later in the system if it's needed for the application.

The Y axis units must also be understood. Is it amplitude, or amplitude spectral density, or power spectral density? For a signal $x(t)$ - where x is either voltage or current and with unit resistance, the power is $x^2(t)$. If the Y axis is in dB then this translates to a factor of 2 in the $log()$ dB calculation. If it's not in spectral density units then correction for the FFT size and/or Window functions may be needed.

If a weighting function was applied in addition to the FFT window function then its impact on measurements must be considered.

In the case of measuring $1/f$ noise by using a data point from the FFT that is below 20 Hz one must consider the impact of a DC signal and the bin spreading from the FFT window. Large FFT sizes, like the 128K point ones used here, in conjunction with window functions with low side lobes are desired.

Since the signal is a random process a single FFT will have a lot of random variation in it. Experimentally somewhere between 64 and 256 averages were observed to be needed to obtain consistent results. A small amount of smoothing of the FFT result, 1/24 octave in our case, further simplifies the FFT interpretation without masking small signals caused by undesirable interference.

This same averaging and smoothing process can mask interference that isn't constant; the experimental setup can detect signals of just a few nanovolts which means issues are to be expected even in a well constructed test system. Validating that the test setup isn't producing contaminated results is critical and in many respects more difficult than collecting the actual data from the parts being tested.

Unexpected issues in the test setup used here included an initial improper ground connection. Even though it was inside of the shielded box, it allowed the fixture to receive a nearby radio broadcast.

The AP515's ability to monitor its input via an attached amplifier/speaker was critical to detecting sources of unintentional interference in the test fixture.

The authors would stress that anyone replicating this experimental method fully validate the results provided by the measurement device if it is not the AP515 used here. It has been observed that in other test equipment FFT results may not be scaled correctly and/or have window function and FFT size limitations that contaminate the low frequency results needed for the $1/f$ estimation.

B Test fixture design

The test fixture of Figure 3 is an accurate summary of the experimental setup, it is not complex and provided useful data to validate the methodology. The details beyond the summary were mostly to facilitate ease of switching the DUT. As discussed in the text accompanying Figure 3, the authors credit Seifert [21] for the fixture design. The lack of the LNA (Low Noise Amplifier) used in [21] was mostly compensated for by the low noise level of the AP515.

The original test fixture design provided for measurement of resistors in a bridge configuration [21] as well as an added test circuit for using the resistors in a typical op-amp amplifier circuit. The latter circuit was not used for the research described here, but could prove valuable for future research. Full construction details can be found on the author's website [30].

With no budget, on-hand materials were used; in this case a cookie tin with the paint sanded off to provide a shielded enclosure. Perf board construction was used, but an obvious improvement would be a simple 2 layer PCB to eliminate the wired connections that provided a path for EMI pickup.

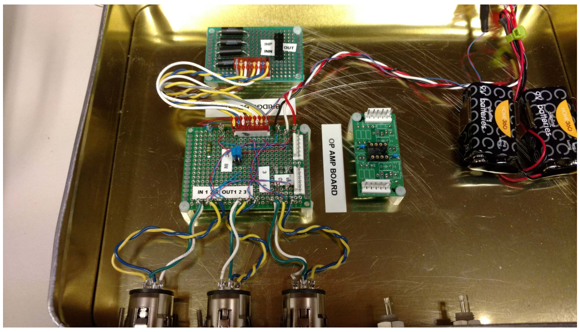

Fig. 5: Test fixture cookie tin. Top PCB is resistor bridge board, XLR connectors at the bottom. Unused op-amp test board on right side.

The resistor portion includes two resistor bridges, one for the reference and the other for the DUT. The reference bridge and the DUT bridge are on the PCB at the top of figure 5.

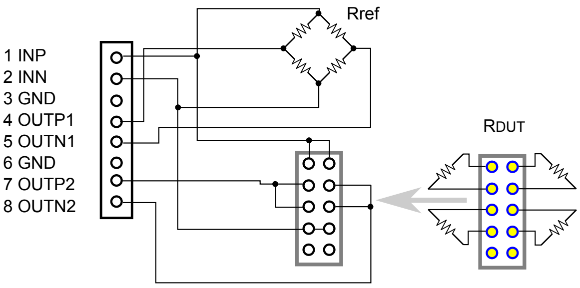

Fig. 6: Schematic of reference resistor bridge and DUT bridge.

The DC voltage is applied across INP and INN pins of figure 6, and the two differential outputs are OUTP1/OUTN1 and OUTP2/OUTN2, with output 1 being the reference bridge and output 2 being the DUT.

Two 9V batteries were used as the DC supply, as batteries generally have very low noise [31]. With the bridge design, any noise from the voltage source appears as common mode noise, which the AP515 removes. The bias supply circuit also added decoupling caps to further filter any coupled noise. By using a bipolar supply the common mode voltage of the bridge is also very small, the marginal error being due to normal resistance tolerance and slight difference in battery voltages.

It was noted that smaller values of resistors presented enough load to the alkaline 9V batteries to cause their output to sag. An improved fixture could use 12V sealed lead batteries. In addition to being able to supply the needed current for an extended period, they could also be recharged. Their series voltage of (nominally) 24V would also provide a larger $1/f$ signal. Low wattage, low value parts will be problematic with higher test voltages.

The test design recommended by Peter Märki's "Thick Film Resistor Flicker Noise" white paper [22] was used (Figure 7) for quickly swapping SMT parts under test.

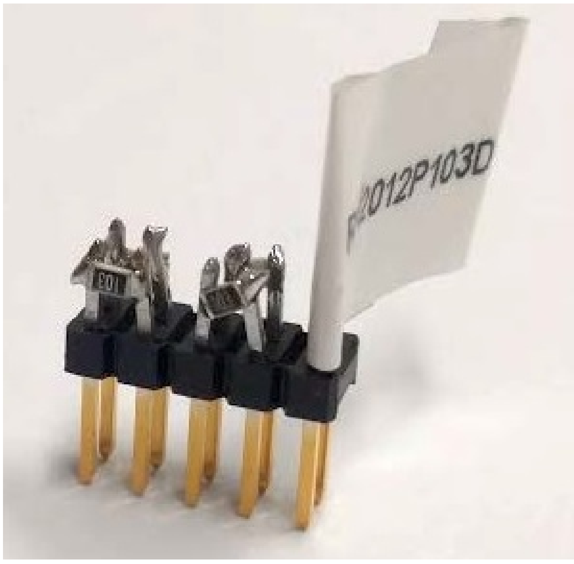

Fig. 7: Header with SMT resistors.

Axial leaded (through-hole) resistors were plugged directly in to the header.

While the AP515 input noise is low, it's high enough to exceed the $1/f$ noise of superior thin film parts. A low-noise amplifier (LNA) as recommended in Seifert's research [21] would be needed. Also see Seifert's paper for a discussion of why more than one LNA is needed based on the value of resistor being measured. A detailed description of another experimental setup for $1/f$ noise can be found in citation [32].

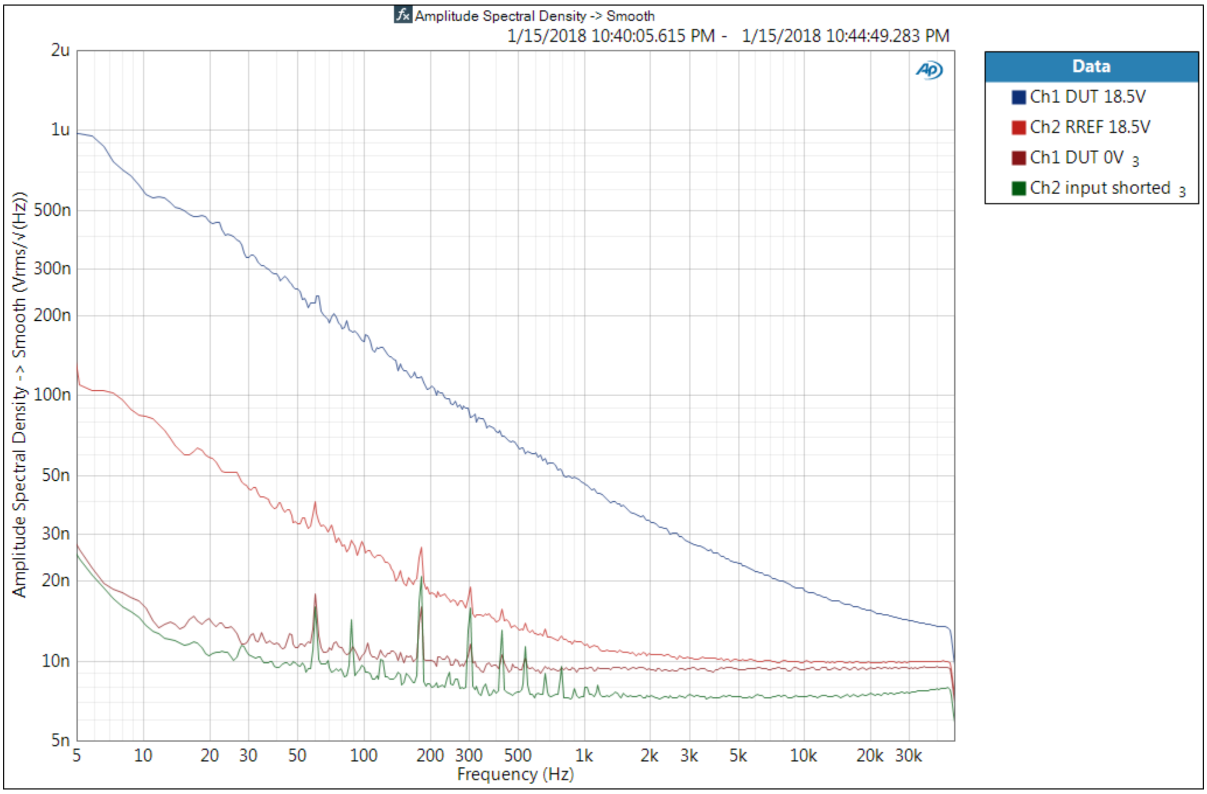

Fig. 8: Yageo 2K thick film 0603 SMD with 18.5V (biased) and 0V (unbiased) with Rref (biased) and input shorted plots for comparison. Smoothed ASD.

C Example data capture and analysis

Figure 8 shows the results of capturing data with an AP515. The DUT is on channel 1 and the reference resistor (2 kΩ Ohmite WN wirewound) is on channel 2. The bottom (green) trace in figure 8 is with input 2 shorted to show the residual instrument noise.

This plot is an amplitude spectral density (ASD) plot so the Y axis units are in volts RMS-root-Hertz. Analysis of the data obtained from the AP515 plot was done using the Excel spreadsheet available from Trump [23] to calculate the NI.

The spikes at 60 Hz and its harmonics would appear to ruin the measurements. However, they can be safely ignored as we only need to pick one representative point in the $1/f$ portion of the curve (i.e. between 5 Hz and about 20 Hz for the bottom most input shorted curve) and a second in the Johnson (flat, white noise) portion, for example, 5 kHz. The increase in noise with decreasing frequency starting around 500Hz shown on the bottom (input shorted, green) curve is from the AP515's inherent $1/f$ noise.

The second line up from the bottom in figure 8 is for a 2 kΩ thick film resistor with no voltage applied to it. The curve shows the higher Johnson-Nyquist noise of the resistor than the AP's residual input shorted (i.e. 0 ohms) value; about 9.5 nV$\sqrt{Hz}$ compared to the AP515's 7.5 nV$\sqrt{Hz}$ residual. With no DC voltage applied to the resistor the $1/f$ noise is that from the AP515's input circuitry.

The third line is the measurement of the biased reference bridge that was built with Ohmite 2.5 kΩ wirewound resistors. This one particular value of resistor turned out to have a high NI which made it convenient for verifying the test setup during data gathering. The slightly higher Johnson noise than the 2 kΩ DUT can be seen.

The fourth (top) line is the data from the 2 kΩ thick film resistor with the bias voltage applied. The $1/f$

noise so dominates this part that the Johnson noise can not be determined.

This plot also illustrates the potential issues with the analog based standard IEC/MIL methodology for NI measurement. This analog test uses a bandpass filter centered on 1 kHz. Many of the low noise parts tested had curves very similar to the two bottom curves of figure 8. There is very little $1/f$ noise energy in the decade around 1 kHz, leading the authors to wonder how accurate the measurements may be given the large range of possible sources of experimental error.

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