Noise floor in ADC testing

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Abstract- The main goal of this paper is to introduce several definitions of noise floor and to show their application in ADC testing with regard to straightforward reading of some basic ADC parameters. The definitions and algorithms can be used for ADC standardization.

I. Introduction

Noise floor is a frequency spectrum parameter that is widely used in ADC testing although it has not been properly defined and described by a formula in any ADC standards yet. IEEE Std 1057-1994 does not mention the noise floor but it generally uses noise or noise level that is not defined. IEEE Std 1241-2000 provides a formula for noise floor computation depending on the number of ADC bits; consequently, such noise floor corresponds to that of the ideal ADC and not to the reality. In the last version of DYNAD (version 3.3, Sept. 2000), the definition of the noise floor is the most precise. Harmonic components, gain and offset errors are not considered there when determining the noise floor and a formula for noise floor computation is also provided. Unfortunately, only white noise is used in this standard and spurious components are not considered there.

The noise floor is commonly understood as the average (sometimes also maximal) power of random noise (i.e. the noise that is freed of any harmonic, spurious and DC components) in frequency spectrum. It implies that the noise floor determines the detection power level under which no weak signals can be discovered. It also determines power uncertainty of evaluation of any spectral component due to noise. So, the noise floor is important information in frequency domain. Once estimated, it can be used e.g. for the detection of strong spectral components.

II. Noise floors

When noise is the product of quantization, the noise floor can be derived using an ADC parameter, *SNR*—signal to noise ratio. If the ADC input signal is a sine-wave signal that spans the full-scale range of the converter, the *SNR* can be expressed using the well-known formula

$$SNR(\mathrm{dBfs}) = 6.02N + 1.76 \tag{1}$$

where N is the number of ADC bits. As the noise is assumed to be white, the value of the *SNR* determines the noise floor level. The *SNR* is often computed for the signal that does not fully cover the ADC full-scale range. In this case, the noise floor, *NF*, has to be corrected for the signal to full-scale ratio

$$\begin{aligned} NF(\mathrm{dBfs}) &= -SNR(\mathrm{dBfs}) \\ &= -SNR(\mathrm{dBc}) + 20\log\frac{signal_{RMS}}{full\ scale_{RMS}}. \end{aligned} \tag{2}$$

When the signal of interest occupies a smaller bandwidth, *BW*, which is less than the Nyquist bandwidth, a digital filter can filter out the noise outside the bandwidth *BW*. In this case, the noise floor is increased by the factor called processing gain

$$NF(\mathrm{dBfs}) = -SNR(\mathrm{dBfs}) - 10\log_{10}\frac{f_s}{2BW} \tag{3}$$

where f_s equals the sampling frequency. Typical example of a digital filter is the DFT algorithm. The DFT acts as a bank of digital filters each of bandwidth f_s/M where M is the DFT length. So, the noise floor in the DFT spectrum is done by

$$NF(\mathrm{dBfs}) = -SNR(\mathrm{dBfs}) - 10\log_{10}\frac{M}{2}. \tag{4}$$

Moreover, if a non-rectangular window is applied to the signal, this formula has to be corrected by the equivalent noise bandwidth, *ENBW*, of the window

$$NF(\mathrm{dBfs}) = -SNR(\mathrm{dBfs}) - 10\log_{10}\frac{M}{2ENBW}.$$

Note that windowing decreases the leakage effect but it also decreases frequency resolution and it worsens the noise floor ($ENBW \geq 1$). Thus, special care should be taken when choosing the window.

Short analysis made above is the basis of the most definitions of the noise floors in ADC testing. In the following subsections, several various noise floors are proposed. All noise floor definitions are summarized in appendix at the end of this paper.

A. Ideal noise floor

As mentioned above, the definition of the noise floor according to the IEEE Std 1241-2000 corresponds to the noise floor of an ideal N-bit ADC

$$NF_{ideal}(\mathrm{dBfs}) = -6.02N - 1.76 - 10\log_{10}\frac{M}{2ENBW}. \qquad (6)$$

Although this value is practically unreachable, if plotted in the amplitude frequency spectrum it shows the limitation of the used ADC (see Fig. 3). The difference between the actual and ideal noise floors also corresponds to the ratio of the actual and ideal noise. This ratio determines how many ADC bits are lost due to random noise (common noise floor) or noise plus distortion (effective noise floor). This information can be directly estimated from the frequency spectrum what is not commonly possible.

B. Thermal noise floor

However precise the ADC is, the noise floor is physically limited by the noise generated by the thermal agitation of the electrons. Such noise is called thermal, Johnson or Nyquist and its power can be computed as

$$P_{thermal}(\mathrm{W}) = K \cdot T \cdot BW \qquad (7)$$

where K is Boltzmann's constant (K=1.381·10^{-23} W/Hz/K) and T equals the absolute temperature in kelvins. The noise floor determined by the thermal noise at room temperature expressed in dBm units can be estimated as

$$NF_{thermal}(\mathrm{dBm}) = -174 + 10\log_{10} BW. \qquad (8)$$

E.g. the thermal noise floor equals –174 dBm in 1 Hz bandwidth and –134 dBm in 10 kHz bandwidth.

dBm units reflect the fact that the thermal noise floor is an absolute number unlike other noise floors that are expressed relatively to the ADC full-scale range. If ADC full-scale voltage, U_{fs}, and input resistance, R, are known, the thermal noise floor can be expressed in dBfs units as

$$NF_{thermal}(\mathrm{dBfs}) = 10\log_{10} K \cdot T \cdot BW - 10\log_{10}\frac{U^2_{fs,RMS}}{R}. \qquad (9)$$

In ADC testing, this conversion is needed for displaying the thermal noise floor in amplitude frequency spectrum of the sampled signal that is commonly plotted in dBfs units there. In case of sampled signal, the thermal noise bandwidth, BW, equals the Nyquist frequency, $f_s/2$. If the amplitude frequency spectrum is computed by means of the DFT algorithm, the processing gain has to be added, too

$$NF_{thermal}(\mathrm{dBfs}) = -10\log_{10}\frac{M \cdot U^2_{RMS,fs}}{R \cdot K \cdot T \cdot f_s \cdot ENBW}. \qquad (10)$$

The difference between the thermal and (dynamic) common noise floors equals the noise figure. A simplified diagram of several noise floors is shown in Fig. 1.

C. Effective noise floor

When the number of ADC bits in (6) is replaced by the effective number of ADC bits, the effective noise floor is obtained

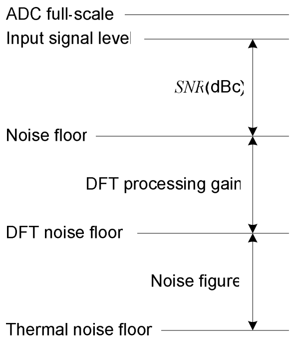


Fig. 1. Simplified diagram of noise floor levels

$$\begin{aligned} NF_{ef}\,(\mathrm{dBfs}) &= -6.02N_{ef} - 1.76 - 10\log_{10}\frac{M}{2ENBW} \\ &= -SINAD(\mathrm{dBfs}) - 10\log_{10}\frac{M}{2ENBW} \end{aligned} \quad . \qquad (11)$$

This noise floor corresponds to overall ADC performance and if plotted in the amplitude frequency spectrum it offers a quick comparison with the common noise floor. If the effective noise floor is noticeably above the common noise floor, the overall ADC performance is considerably limited also by spurious and/or harmonic components.

D. Common noise floor

If the noise in amplitude frequency spectrum is freed of harmonic and spurious components, the average power of this noise corresponds to the common noise floor. In ADC testing, a parameter called the signal to non-harmonic ratio, *SNHR*, is frequently used. Accordingly, the *SNHSR* parameter can represent the signal to non-harmonic non-spurious ratio. Using this parameter, the common noise floor is given by

$$NF(\mathrm{dBfs}) = -SNHSR(\mathrm{dBfs}) - 10\log_{10}\frac{M}{2ENBW}\,. \qquad (12)$$

The common noise floor represents the average random noise power in frequency spectrum. The level of the common noise floor can be advantageously used for further data processing e.g. for distinguishing strong and weak components in the frequency domain. Unfortunately, strong spectral components are needed to be known and their power subtracted from random noise power before the computation of the common noise floor.

E. Dynamic (common) noise floor

The computation of the common noise floor by formula (12) assumes white noise. If the noise is colored, the noise level computed by this formula does not follow frequency dependence of random noise. Thus, it is advantageous to compute the common noise floor dynamically in dependence on frequency.

The approximation by a simple polynomial is mostly sufficient. As the noise in dependence on frequency usually varies in logarithmic scale, the approximation is more precise when also done in logarithmic scale. Note that such approximation is biased due to the logarithm. If the variance of amplitude frequency spectrum is decreased by averaging (Welch method), the bias is essentially reduced.

III. Recognition of strong spectral components

After the dynamic noise floor is determined, strong spectral components can be recognized as the components bigger than a certain threshold above the dynamic noise floor. As already mentioned, the problem is that strong spectral components are needed to be known for the determination of the dynamic noise floor.

A solution can be to search for strong spectral components and dynamic noise floor iteratively (see Fig. 2). In the first step, the number of significant harmonic components is estimated. The dynamic noise floor is computed from the averaged power spectrum freed of harmonic components. Strong spectral components can be recognized using a specific threshold, then. These components are excluded from the amplitude frequency spectrum for the next estimate of the dynamic noise floor. Fortunately, no iteration is mostly necessary and the number of iteration does not exceed two in practice because the noise power usually dominates the power of spurious and harmonic components.

The proposed algorithm can be applied even for windowed signals. If several spurious components appear in narrow bandwidth, they can increase local dynamic noise floor. However, the dynamic noise floor can be decreased in next iteration(s); if not, the spectral character of spurious components is close to random noise in this bandwidth; consequently, they are also processed as random noise.

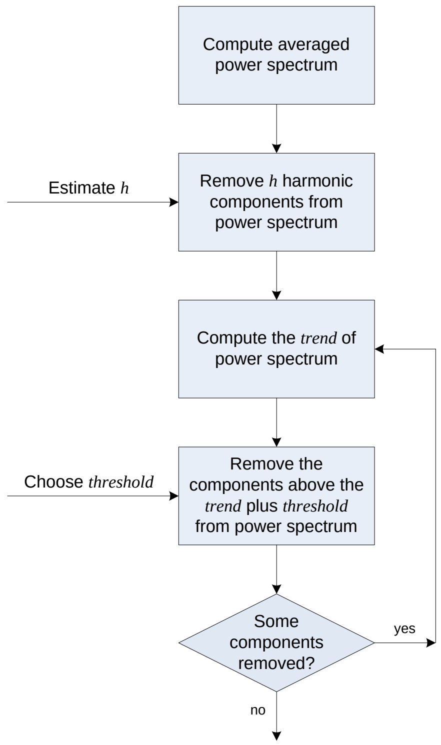


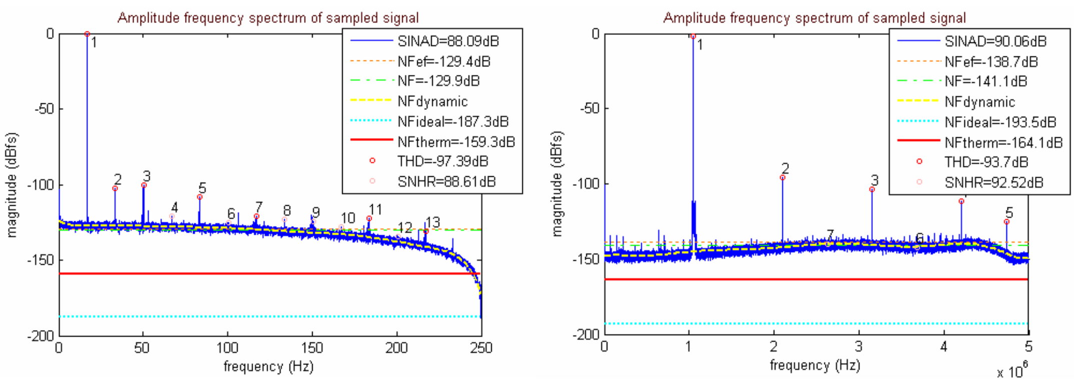
Fig. 2. Block diagram of the proposed algorithm

IV. Examples

The proposed noise floor definitions were applied on experimental data gained by acquisition by several different ADCs for pure sine-wave input signals. The acquired data were used for the computation of averaged power spectra (Welch method) from which amplitude frequency spectra were computed. Noise floors as well as the most important spectral parameters of the tested ADCs (*SINAD*, *THD* and *SNHR*) were estimated and shown in amplitude frequency spectrum.

Fig. 3a shows the computed amplitude frequency spectrum of an AD7793 evaluation board. The overall ADC performance expressed by the *SINAD* is obviously given by dominating ADC noise (plus spurious components) as $SINAD \cong SNHR$. This fact can also be directly estimated from no significant difference of the effective and common noise floor levels displayed in amplitude frequency spectrum. The only distinction between these two ways of estimation is that unlike the *SNHR*, the common noise floor does not contain the power of spurious components; their power is usually negligible in practice, though.

The dynamic noise floor was gained by the approximation of 9th order polynomial. The order of nine was found out to be the best choice in practice. Lower orders do not approximate local average



a) AD7793 evaluation board (16 bits, f_s=500 Hz, 64 kSa)

b) PXI NI-5922 (24 bits, f_s=10 MHz, 256 kSa)

Fig. 3. ADC noise floors plotted in amplitude frequency spectra

power of noise well and higher orders react too quickly to any change in spectrum. Note good approximation of noise trend and significant difference of common and dynamic noise floors.
Strong spectral components were found out in the frequency spectrum with the threshold of 8 dB from the dynamic noise floor. Weak harmonic components were signed by lighter color in the amplitude frequency spectrum. The optimal threshold level depends on random noise variance and the number of averages. In practice, the threshold in the range 6–10 dB is recommended.

The level of the ideal noise floor shows that the actual ADC performance is much bellow its nominal resolution. Only at higher frequencies, the dynamic noise floor approaches the ideal noise floor due to strong ADC internal digital filtering. The thermal noise floor level indicates that the ideal noise floor is unreachable in this test configuration because of the thermal noise.

Similar conclusions can be made in case of amplitude frequency spectrum of the PXI NI-5922 digitizer shown in Fig. 3b. The effective noise floor level is noticeably above common noise floor. It means that the overall ADC performance is considerably influenced also by harmonic distortion. The dynamic noise floor is relatively close to the thermal noise floor, especially at low frequencies; this indicates a good ADC noise performance. Huge gap between the ideal and dynamic noise floors implies that much lower number of nominal ADC bits would be sufficient for the same ADC performance.

V. Conclusion

In this paper, several noise floors were characterized, defined and described by formulae. The usage of the noise floors was shown on practical ADC measurements and quick reading of some basic ADC parameters by means of noise floors was stressed. The application of the noise floor was shown on the detection of strong spectral components.

References

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Appendix: Noise floor definitions

Ideal noise floor
Average power level of quantization noise of an ideal ADC in the frequency spectrum.

Thermal noise floor
Average power level of the noise generated by the thermal agitation of the electrons over a given bandwidth in the frequency spectrum.

Effective noise floor
Average power level of ADC noise, distortion and spurious components in the frequency spectrum.

Common noise floor
Average power level of the ADC noise without spurious and harmonic components in the frequency spectrum.

Dynamic (common) noise floor
Trend of average power level of the ADC noise without spurious and harmonic components in the frequency spectrum.