Static and Dynamic A/D Converter Nonlinearity

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Abstract-The ADC's static and dynamic nonlinearity with relation to harmonic distortion and parameters describing the nonlinearity are discussed. The commonly used description by INL and hysteresis is acceptable only if the dynamic nonlinearity is significantly lower than the static nonlinearity. The significance of dynamic nonlinearity is presented on the measurement and the analysis based on complex spectrum is demonstrated. We call the attention to more detailed tests of ADC according to the dynamic nonlinearity and definition of an optimal working point with maximal SFDR.

I. Introduction

The ADC is still a limiting part of the wide bandwidth and high dynamic range systems. The noise is not the limiting parameter, the achievable ADC's SNR level is higher than 150 dBFS/√Hz and is comparable with the best analogue circuits. The problem is in harmonics and spurious. The wide bandwidth system with spurious free dynamic range higher than –100 dBFS is hard to achieve. The contributions and standards about ADC measurement are mostly concerned in different kinds of integral nonlinearity (INL) measurement and in the relation between harmonic distortion and INL [1,2]. Some contributions describe how to minimise ADC's harmonic distortion by post-correction [3,4]. However, the practical limitations of these methods are not mentioned and so this is more a good theory than a real increasing of SFDR performance.

The basic disadvantages of the used approach are: i) The INL description neglects the out of phase components and the ADC nonlinearity may be underestimated [5,6]. ii) The INL describes static and some dynamic ADC nonlinearity and it is impossible to simply analyse the part corresponding to dynamic nonlinearity. iii) Some post-correction of ADC has sense if it is valid in a sufficiently broad area of input parameters only.

II. Nonlinearity of ADC

The harmonic distortion is given by the ADC non-linearity [7]. The nonlinearity can be divided into static and dynamic. If we suppose a rather ideal ADC with static nonlinearity only, then INL is the best description of ADC properties and this must be valid:

- The result of an INL measurement is independent on an input signal type, amplitude and frequency. With a lower amplitude we achieve a corresponding lower part of INL. The measurement is quite reproducible.
- The high order harmonics terms may be transferred to noise with a sufficient dither or input noise not coherent with the sampling frequency. The same theory is valid as in the case of quantization [7], only the noise level must be higher. This is valid, even if some missing code exists.
- Some transfer function exists between the input (x) and output (y) signal as:

$$y = f(x) = \sum_{i=0}^{n} a_i x^i , \qquad \text{where x is the input signal.} \tag{1}$$

- All harmonic terms must be in phase with the input signal, because it is valid:

$$(\cos\alpha)^n = \frac{1}{2^n}\sum_{k=0}^{n}\binom{n}{k}\cos\alpha(n-2k). \tag{2}$$

At such an ADC the correction of INL is advantageous, it eliminates corresponding harmonic distortion and significantly improves SFDR.

Rather different conditions are at a real ADC, where the dynamic nonlinearity may be significant. In this case INL describes the static nonlinearity together with the part of dynamic nonlinearity that is independent on the direction of a signal change (for example limited slew rate, independent on polarity). Such INL is valid only for a given input signal, and harmonics terms corresponding to INL are in phase with an output signal. The rest of dynamic nonlinearity (i.e. the nonlinearity that is dependent on the direction of a signal change) is represented by hysteresis and produces the out of phase components.

The description of ADC nonlinearity based on INL and hysteresis has these disadvantages:

- INL describes the static ADC nonlinearity together with some part of dynamic nonlinearity. If we go to the details, even some part of static nonlinearity may be in hysteresis. Explanation: INL measured with an input harmonic signal represents the in phase terms with a carrier [5,6]. If ADC has significant symmetric dynamic nonlinearity, it produces the phase shift of the carrier and some parts of harmonics terms given by static nonlinearity occur out of phase. With the histogram test the static and dynamic terms cannot be differentiated. With the test based on a complex spectrum and if the phase shift of the carrier is known (according to the phase shift between the carrier and sampling frequency on the input and output) the static and dynamic nonlinearity may be differentiated.
- The in phase and out of phase terms have different descriptions – INL and hysteresis. Some way is to use INL in a complex form, i.e. the transfer function with complex coefficients.
- The INL description may be useful for ADC producers, it was very important in past, when missing codes existed, it may be useful at dc measurements, but it has not much sense for the ADC users that are working in high frequency area. For them the maximal levels of harmonics terms and SFDR are important and these parameters are given by a complex spectrum.
- The INL and hysteresis did not give the sufficient information at special tests, as the undersampling application, envelope and beat frequency test.

The ADC nonlinearity correction has been often used recently[3,4]. It significantly increased the ADC performance, but if dynamic correction is used (i.e. the correction is valid for a given input signal only), some problems occur. Such a correction increases the performance in the area where it was adjusted but it decreases the performance in other areas and, moreover, the analysis of such ADC imperfections is impossible to be carried out by a user that does not know the correction. Even if the dynamic correction is known, how to measure and analyse the possible origins of ADC's dynamic nonlinearity at the presence of rather strong, corrected, artificial dynamic nonlinearity?

The new methods how to characterise the ADC nonlinearity have been searched for [8,9]. But why not to use the best description of ADC nonlinearity according to users; i.e. the description of amplitudes and phases of harmonics terms, regarding to measurement conditions? The description based on a complex spectrum determines not only ADC parameters but also represents the acquisition system performance.

III. Measurements and results

We do the next measurement in order to test, if some correction may increase the SFDR in undersampling applications at a given ADC. The used ADC was AD6644 (Analog Devices, 14 bits). The input signal was 90.031425 MHz, amplitude FS-2 dB, pure harmonics or with an analog dither (white noise). The sampling frequency was coherent with the input, 29.982720 or 59.96544 MHz. In the following text we will mention 30 and 60 MHz fs. The basic block of data was 64 K, it was repeated 400 times to achieve a noise floor in a frequency domain without dither –130 dBFS. With dither the noise floor was –120 dBFS. The data with fs=60 MHz were decimated by two before the processing, to achieve identical data as with fs=30 MHz.

Some amplitude spectra are in Fig. 1. Every spectrum is a result obtained from two measurements, the sum or the difference of two phase corrected complex spectra. In the sum the noise is the same as in the difference and the difference represents the reproducibility of the results. In Fig. 1 a), b) the sum is presented with fs 60 MHz, a) pure input, b) input with dither. We may see significantly high order harmonic terms, in all Nyquist band. The used dither does not transfer the harmonics terms to noise, its influence seems to increase the noise floor only. The differences of the same measurements are in c), d). In c) the difference of two measurements without noise is presented, in d) of two measurements with noise. The reproducibility of the measurement, if the input signal is equal, is good; the differences in the carrier are lower than –70 dB. The presence of other discreet signals than harmonics is tested in f), e). The a), b) figures, without bins corresponding to harmonics, are in e), f). The non-harmonics discreet signals are below –110 dBFS and correspond to non-reproducible signals from c), d). In g), h) the test of reproducibility is presented, when the measurement parameters are not quite identical. In g) the difference between measurements with noise and without

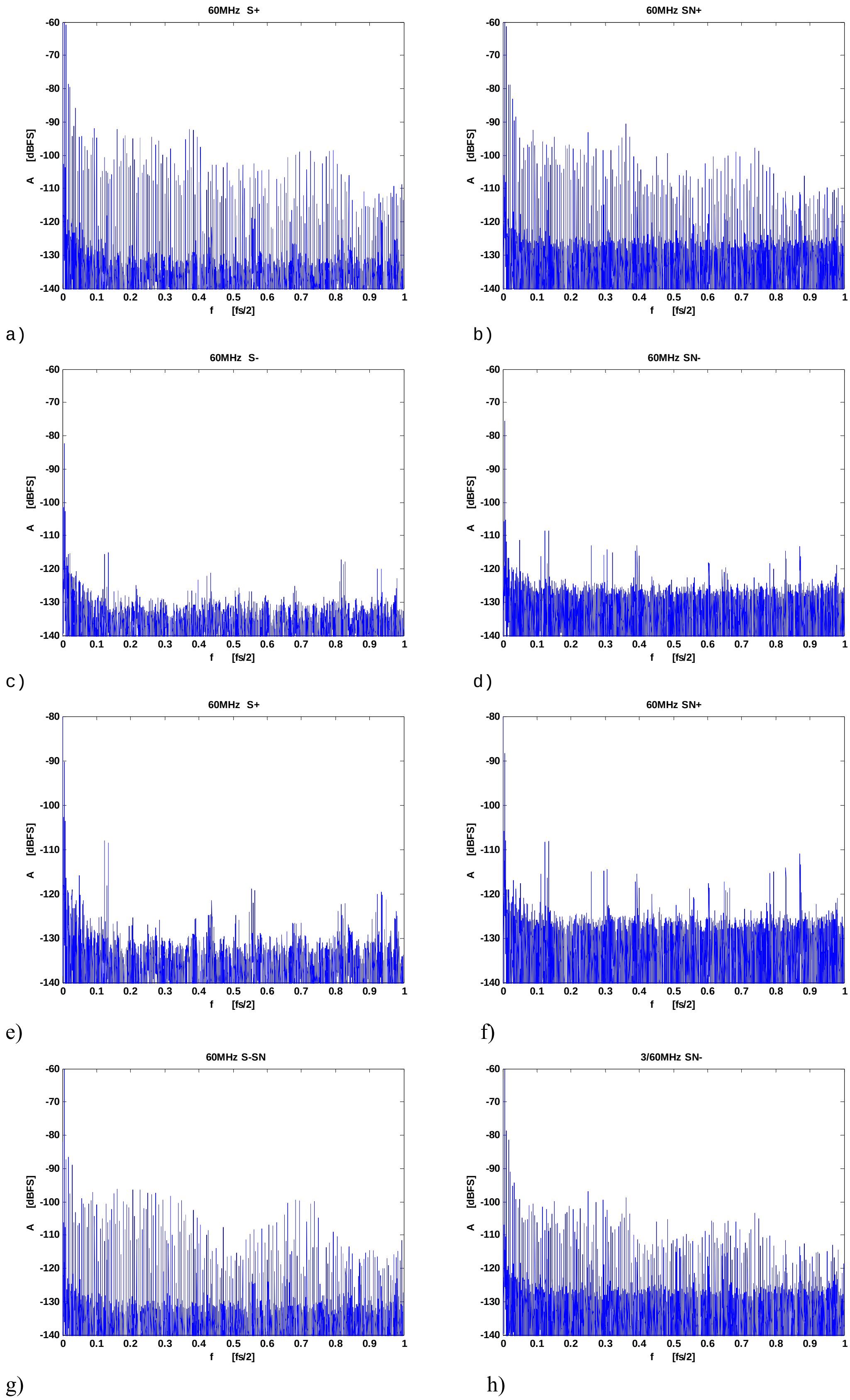

Figure 1. Amplitudes, the sum (a, b, e, f) or difference (c, d, g, h) of two complex phase corrected spectra. Input without dither (a, c, e), with dither (b, d, f, h), on g) the difference of one measurement with dither and the second measurement without dither. Sampling frequency is 60 MHz during the whole measurement, except h) where one measurement has fs=30 MHz. The test of nonharmonics distortion is in e), f) – the harmonics terms were eliminated by post processing.

noise is shown; in h) the difference of measurements with noise is presented, but one measurement was with fs=60 MHz and the second with fs=30MHz.

The more detailed analysis of the measurement is in Tab. 1. The mean power and the mean power of in phase and out of phase harmonic terms in groups for different measurement are in Tab. 1. The differences of measurements with the identical input signal and identical fs are not there. In this case the reproducibility is good and the power is comparable with the noise power.

During the measurement the possible small phase shift of the carrier relatively to fs was not analysed, the time and phase synchronization among the input signal, fs and start of acquisition was not possible. That is why we cannot determine the exact static and dynamic part of ADC nonlinearity. The analysis is based on the in phase and out of phase power.

	Mean power			Mean in phase power			Mean out of phase power		
Order	2:5	6:20	20:50	2:5	6:20	20:50	2:5	6:20	20:50
	Fs=60 MHz								
S+	-67	-94	-99	-68	-95	-102	-73	-100	-103
SN+	-67	-95	-99	-68	-97	-102	-74	-100	-104
S-SN	-88	-101	-101	-93	-104	-104	-91	-106	-106
	Fs=30 MHz								
S+	-64	-99	-112	-66	-100	-113	-68	-107	-122
SN+	-65	-100	-112	-67	-106	-113	-70	-102	-122
S-SN	-82	-106	-118	-84	-108	-119	-85	-110	-128
	One fs=60 MHz, second fs=30MHz								
S-	-79	-101	-106	-84	-105	-108	-82	-105	-110
S+	-65	-97	-104	-67	-98	-106	-70	-106	-108
SN-	-83	-101	-104	-86	-104	-106	-85	-105	-109
SN+	-67	-99	-106	-68	-101	-109	-72	-103	-110

Tab. 1. Mean power of harmonics terms in dBFS. S+ sum, S- difference of two measurements without noise; SN+ sum, SN-difference of two measurements with noise; S-SN difference, one measurement without noise, second with noise.

IV. Discussion

The harmonics terms may be divided into low order harmonics (in the Tab. 1 represented by the group of the order of 2-5) and high order harmonics (groups of the order of 6-20 and 20-50). The low order harmonics have a higher amplitude, more sources of origin and their amplitudes differ significantly between summed and differentiated spectrums. All harmonics are well reproducible, if the conditions of measurement are equal. The mean power of difference of low harmonic terms is below –110 dBFS, at high harmonic terms below –120 dBFS, i.e. nearly on the noise level.

With fs=60 MHz the mean power of high harmonics terms is higher than with fs=30 MHz. The same is valid for the power of out of phase terms. This corresponds with a theoretical assumption, where fs=60 MHz represents the envelope test, with maximal influence of a sample and hold circuit and this represents the high order dynamic nonlinearity.

The significant out of phase power is in any spectrum, i.e. the measured ADC has significant dynamic nonlinearity. If the conditions of the measurement are not quite identical, the high order harmonics term changes randomly their amplitude and phase. It is not possible to found some usable correction that would significantly increase SFDR for real application. With optimisation of fin/fs ratio the SFDR round –100 dBFS may be achieved, but hardly better.

The description of ADC nonlinearity, based on a complex spectrum, has following advantages comparable to INL and hysteresis:

- It represents the parameters important for the user, these are the system (not only ADC) parameters.
- The reproducibility and the dependence on the input parameters may be simply tested by subtracting two complex spectra.
- The significance of dynamic nonlinearity is simply determined comparing the power out of phase terms with the power in phase terms.
- If the phase shifts between the carrier and input and output signal are measured, the pure dynamic and static nonlinearity may be determined. This is valid, if we suppose the ADC as one black box, not as a serial connection of different blocks.

V. Conclusion

The description of ADC nonlinearity by INL has sense if and only if the static nonlinearity is significantly bigger than dynamic. But this is not valid at real applications of a present, fast ADC. At such an ADC the dynamic nonlinearity is significant, INL depends on the input signal and the hysteresis must be measured. The description based on a complex spectrum gives better overview about importance of dynamic nonlinearity, reproducibility and before all, it is a system parameter that describes the quality of a system not only the ADC parameter.

The ADC post correction of static nonlinearity increases significantly the ADC performance. But the dynamic correction, especially the correction based only on minimal harmonic distortion with representative input signal, may be dangerous. It increases the performance for a given signal but it decreases it for some others. It needs a more detailed analysis in future, the validity and the dependency on input signal should be always mentioned and before all, such a correction must go out from ADC design.

According to the presented measurements, the high frequency broadband system with SFDR better than –100 dBFS is still hard to achieve without carefully chosen frequency plan. The way for future is the better understanding of different sources of dynamic nonlinearity and concerning on the measurement of a complex spectrum.

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