Dynamic range and acquisition system

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Abstract: The limitation of the dynamic range given by noise and spurious signals is discussed. Attention is paid to the proper unit [dBFS/√Hz] in the case of noise limitation. On the example of the acquisition system it is presented how to determine the limiting part of the system.

Introduction

Dynamic range describes the range of the input signal levels that can be reliably measured simultaneously, in particular the ability to accurately measure small signals in the presence of the large signals. According this definition the dynamic range may be a useful parameter of any system and is the very important parameter of the measurement system. There exist some applications (spectral analysis, nuclear magnetic resonance or tomography, communication by power net, etc.) where the dynamic range should be as high as possible. But how high may be the dynamic range? So simple question and mostly remain without reply.

Dynamic range limitation

The maximal signal is always limited in the acquisition system. It is limited by system full scale signal, that is mostly equal with ADC full scale signal. The analysis of a small signal is limited by two independent error signals: system noise floor and spurious signals. The dynamic range must be analyzed independently according to this two error signals.

The dynamic range is mostly given in dB. On example in the draft of ADC standard – DYNAD (Dynamic characterization and testing of analogue to digital converters) the dynamic range is defined as a full scale amplitude to peak noise floor and for a N bit ideal ADC is equal to ideal SNR [1]:

$$DR = 6.021 \times N + 1.763 \quad [dB]. \tag{1}$$

The dB unit is the good unit in conditions the analysis according to spurious signals is made, but not if the limitation by noise is supposed. With the neglected passband, as it is in Eq. 1, it is not possible to state how high is the maximal achievable dynamic range, what is the dynamic range of acquisition system and what is the needed dynamic range according to input signal.

Eq. 1 is valid in the time domain in the case that no digital filtering nor the analysis in the frequency domain is used. We can say, that Eq.1 describes the broadband signal analysis in the time domain. But such applications do not need the high dynamic range. The high dynamic range is needed at bandpass signal analysis, where only corresponding noise (bandpass noise) should be supposed. Such a case is described by unit suggested by Hilton [2], as the ratio of the full-scale signal and noise power per hertz [dBFS/√Hz]. The advantages of this unit are:

- The unit describes the real achievable dynamic range of the system. So the different systems can be compared.
- The same unit describes the behavior of both digital and analog parts, allowing identification of the dominant contribution.
- The system can be optimized according to ADC, sampling frequency, power supply, etc.
- The needed dynamic range can be simply defined if the parameters of input signal are known.

- The contribution of different methods and algorithms can be defined by this unit.

Limitation by noise

First we analyze the simplest acquisition system, i.e. the system without input preamplifier. In this case the dynamic range is limited by ADC and the dynamic range in dBFS/√Hz is:

$$DR = SNR + 10 \times \log(fs/2), \tag{2}$$

where SNR is ADC dynamic range in dB:

$$SNR = 6.02 \times Neff + 1.76$$

while fs is the sampling frequency and Neff is the number of ADC effective bits. If SNR does not depend on fs, the maximal dynamic range corresponds to maximal fs. If some coupling between analog and digital part exists, the SNR depends on fs and the optimal fs is given by maximum of Eq. 2.

If the preamplifier is used, the dynamic range may be limited by ADC or by preamplifier and is:

$$DR_{AQ} = 10 \times \log((FS/2.8)^2 / (Pn_R + Pn_{OP} + Pn_{ADC})) + 10 \times \log(fs/2) \tag{3}$$

where Pn_R, Pn_{OP}, and Pn_{ADC} are output noise powers of the input resistor, preamplifier, and ADC respectively. Pn_R and Pn_{OP} are the function of the used gain of preamplifier and there exist some cut-off gain G_c, given by:

$$Pn_R (G_c) + Pn_{OP} (G_c) = Pn_{ADC} \tag{4}$$

If the gain of acquisition system is lower than G_c , than the dynamic range is limited by ADC. If the gain is higher, then the dynamic range is limited by preamplifier.

Similar results are achieved, if the noise figure of the acquisition system is analyzed. The results are presented in Fig. 1 and 2. In this case the broadband low noise preamplifier with OPA687 and an ideal ADC with SNR=75 dB, fs=66 MHz, and FS=2 V were supposed. The parameters of ADC correspond to the parameters of AD6644. In the case of noise figure analysis, we suppose no problems with impedance matching on the input of ADC and no aliasing of the input thermal noise. If we use the term noise figure of ADC, the cut-off gain is given by:

$$G_c = NF_{ADC} + NF_{OP} \tag{5}$$

where NF_{ADC} and NF_{OP} are noise figure of ADC and the preamplifier respectively.

As some conclusion of this part can be stated:

- The dynamic range of the acquisition system is given by Eq. 3.
- The system dynamic range should be higher than signal-to-noise ratio of the input signal (SNR according to the maximal signal).
- If system dynamic range is lower, the acquired data are distorted by the acquisition system. The bottleneck of the system is determined by the used gain.

Limitation by spurious signals

The spurious signals are mostly more dangerous than the noise. They have a higher amplitude than noise and their amplitude does not depend on the used passband. Even with accumulation we can not suppose, that they will be eliminated. Spurious signals are given by all non linearity and their main source of them is ADC. According to their origin we can divide spurious to these groups:

a) Spurious signals given by quantization. If the input signal of an ideal ADC is noiseless, the quantization error is not noise, but a set of spurious. This spurious can be fully

transferred to noise, if the input signal includes a noise with an amplitude at least 0.35 LSB rms [2,3].

b) Spurious signals given by DNL of ADC. Corresponding spurious can be again transferred to noise, but not fully in all cases and the noise amplitude must be higher. If there exist missing codes, the elimination is sometimes not possible [3].

c) Spurious signals given by limited slew rate of sample and hold circuit. Such spurious can not be eliminated by input noise or by dither. The only way is to use faster ADC or to change the frequency plan. The frequency of the input strong signal must be moved out of the odd multiples fs/2 [4].

There exist more other sources of spurious signals, as the coupling between digital and analog part, the coupling with a power supply, etc. The analysis of spurious signals is neglected not only in drafts of ADC standards, but also in literature.

Other limitation

A constant amplitude of the full scale signal and constant ADC output noise were supposed in the previous analysis. This is not generally valid. The full scale amplitude may depend on ADC frequency response. The identical attenuation of the strong and weak signals can be supposed and if this attenuation is significant, it must be subtracted in Eq. 3.

The ADC output noise is not constant, if there exist some jitter in acquisition system. We must count with corresponding error signal:

$$P_{jitter} = 2 \, (\pi \times A_{in} \times f_{in} \times dt)^2 \qquad (6)$$

where A_{in} and f_{in} are the amplitude and frequency of the input signal respectively and dt is the rms of jitter.

Conclusion

The dynamic range is given by two independent parameters - limitation by noise and limitation by spurious signals. The limitation by noise is not possible to be expressed by dB, only with the unit dBFS/$\sqrt{Hz}$ the real dynamic range is given. With this unit the systems can be compared and the analysis of needs and the system optimization may be done. The achievable dynamic range is at present 150 dBFS/$\sqrt{Hz}$.

In the area of noise limitation all theoretical problems are known and the only question is, when the proper unit will be used. The working group of IEEE TC-10 promised to include this unit in the IEEE Std 1241. In the area of spurious free dynamic range there exist more theoretical questions how to minimize spurious signals and the needed analysis has not been done yet.

References:
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2. H.E. Hilton: A 10-MHz ADC with 110-dB linearity. Hewlett-Packard Journal, vol. 44, No.5, Oct. 1993, pp.100-112.
3. M. Villa, F. Tian, P. Cofrancesco, J. Halámek, M. Kasal: High resolution digital quadrature detection. Rev. Sci. Instrum., vol. 67, No. 6, June 1996, pp. 2123-2129.
4. J. Halámek, M. Kasal, P. Jurák, M. Villa, P. Cofrancesco: Frequency bandwidth and jitter measurement. Proc of ISDDMI'98, Naples, Italy, Sept. 1998, pp. 393-398.
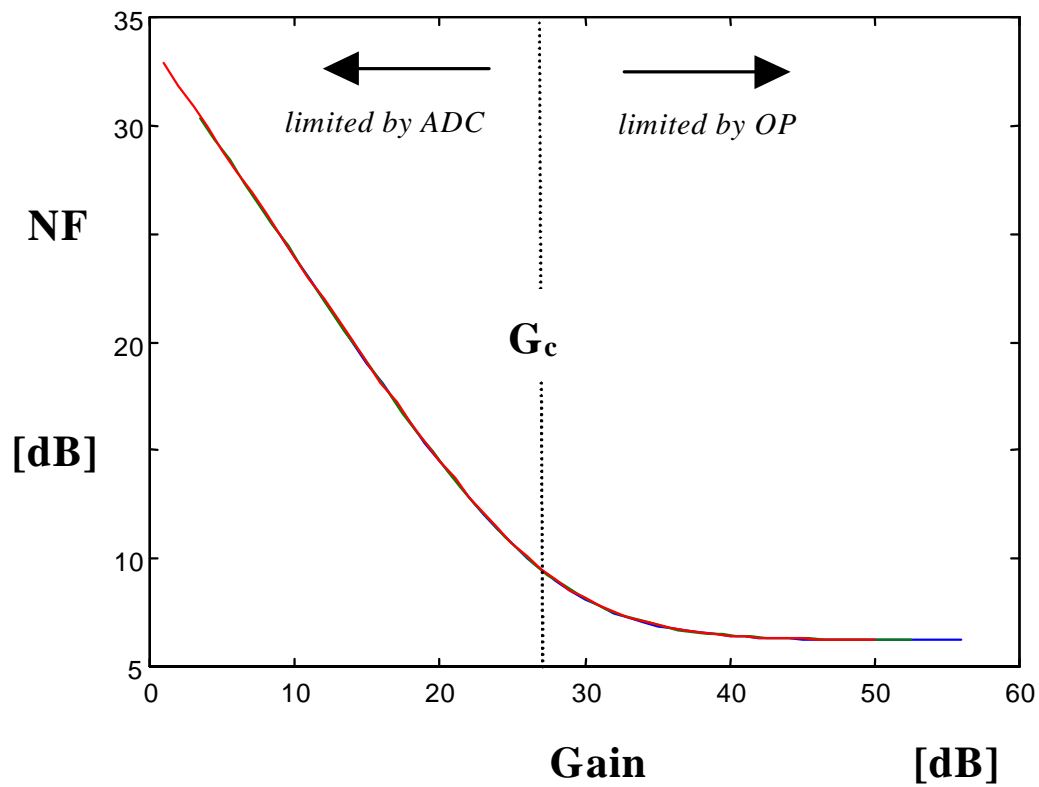
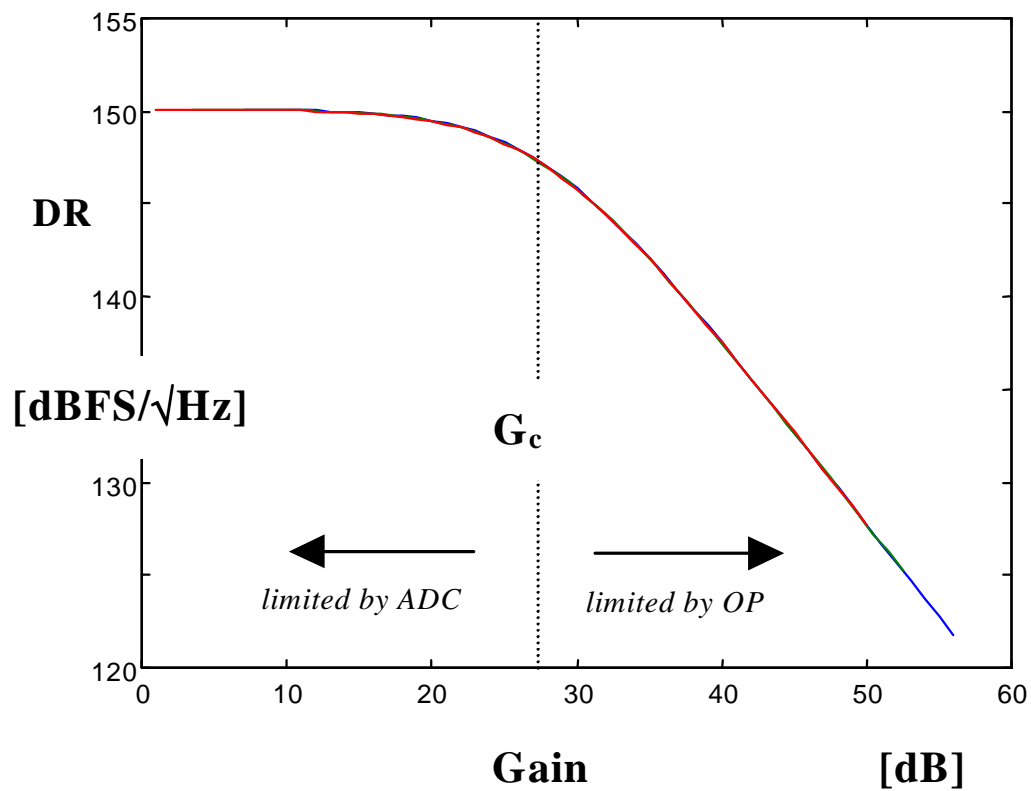Fig. 1. The noise figure of the acquisition system as a function of the used gain.

Fig. 2. The dynamic range of the acquisition system as a function of the used gain.