

ASPECTS OF ADC EFFECTIVE RESOLUTION: DEFINITIONS AND MEASUREMENTS

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Abstract – The article describes some aspects of understanding, defining and measurements of effective resolution of Analogue-to-Digital Converters. The disadvantages and misleading results of commonly used definition are shown and possible solutions are discussed. Finally, one new solution is given and arguments for its correctness and usability are collected.

Keywords: ADC, effective resolution, effective number of bits

1. INTRODUCTION

Analogue-to-Digital Converters are used almost in all contemporary measuring devices to interface the analogue world (represented by chain: measured quantity, sensor, analogue pre-processing) and digital core of the instrument. Several parameters are used to describe ADC. Some of them refer to ideal behaviour of ADC (nominal number of bits, conversion rate), some of them refer to impairments of the real converter (Differential and Integral Non-linearity, Signal-to-Noise Ratio, Effective Number of Bits, Effective Resolution etc.). Although widely accepted standards [1,2] exist, the universal definition of Effective Resolution of ADC does not exist.

2. CURRENT STATUS

To work further with description of ADCs, let us define the following terms:

N -bit ADC with input range FS [V] has a quantisation step equal to

$$q = \frac{FS}{2^N} \quad (1)$$

In case of ideal ADC, the value of Effective Number of Bits (ENOB) is equal to N . Otherwise ENOB is usually defined as [1]:

$$ENOB = \log_2 \frac{FS}{\sigma \cdot \sqrt{12}} \quad (2)$$

where σ means rms conversion error that in case of real ADC includes not only quantization error but also differential and integral non-linearity (and depends generally also on input signal frequency or occupied frequency band, respectively). Similarly, the intuitive understanding of the term Effective Resolution is obvious. The result, when given in voltage units (for ADC that deals with input voltage), should mean the rms value of smallest differences in input signal that could be resolved by the ADC, assuming that all code words and input signal slopes etc. has been covered/involved during the experiment. Moreover, it should be possible to recalculate the result to bits. In this case, for ideal ADC the result has to be again N . The factor determining effective resolution is noise, either quantisation noise or intrinsically analogue.

Unfortunately, those simple requirements are not met by currently used definitions. The basic one that is rather misleading says [3]

$$ER = \log_2 \frac{FS}{RMS\ NOISE} \quad (3)$$

where ER means Effective Resolution (bits) and $RMS\ NOISE$ is rms value of noise on input of ADC converter. This is obviously wrong since numerator contains kind of peak-to-peak parameter and denominator contains kind of rms value. An easy example - experimental results - how to obtain ER higher than nominal number of bits N (of course without further signal processing like averaging) is given in Tab. 1.

There were two attempts to improve this situation published [4], [5]. The first possibility deals with numerator modification. It assumes that the ADC converter is used to convert full-scale sine wave signal and the factor $2^{-1.5}$ is introduced to convert peak-to-peak value to rms value of corresponding harmonic signal:

$$ER_1 = \log_2 \frac{\frac{FS}{2\sqrt{2}}}{RMS\ NOISE} = \log_2 \frac{FS}{RMS\ NOISE \cdot \sqrt{8}} \quad (4)$$

The alternative approach modifies directly denominator in order to change rms-type value to peak-to-peak-type value. It assumes uniformly distributed noise that allows to recalculate rms value to peak-to-peak value by means of multiplying by $12^{-0.5}$:

$$ER_2 = \log_2 \frac{FS}{RMS\ NOISE \cdot \sqrt{12}} \quad (5)$$

The noticeable similarity with ENOB definition (2) is interesting. This relation is applicable to the wider number of cases since the only condition of its applicability is the uniformity of noise distribution. There are no limitations or expectations given for input signal in this case. However, it is easy to understand that in case of e.g. normally distributed noise (Gaussian noise) such definition is useless because no peak-to-peak value is applicable.

3. MEASUREMENT METHODS

The effective resolution can be determined either by suitable time-domain or histogram method. Goal of such measurement is the noise parameterisation. Histogram method allows determining even the amplitude distribution of noise (see Fig. 1).

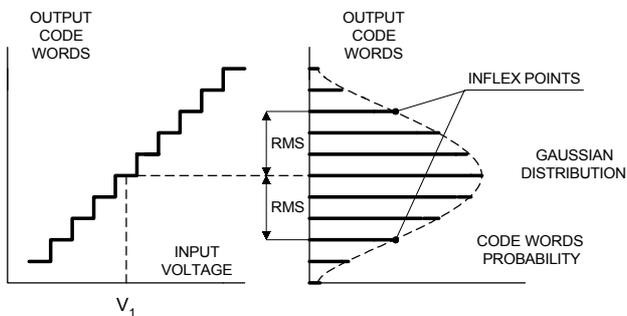


Fig. 1. Code words histogram

An example of Effective Resolution measurement is given on the Fig. 2, that describes the arrangement used for measurements on AD7710 (24-bit Σ - Δ ADC by Analog Devices). The developed measurement system consists of the group etalon Standard Cell Battery TINSLEY 5644B with 10 Weston cells that provides nominal voltage 1,0187 V each. Lower voltages are derived using passive divider based on manganine resistors. Output voltages of divider have been measured using digital multimeter Wavetek 1281 that provides 8,5 decade resolution. Its error (within the range of 10 V) is 0,5 ppm of reading and 0,1 ppm of FS. Always 10^6 samples have been chosen for averaging.

Measurements have been performed at the gain settings 1 to 128 on the input voltages in 0, 1/8, 1/4, 3/8, 1/2, 5/8, 3/4, 7/8 of FS. The range of internal ADC's notch frequency covered the interval from 10 Hz to 1 kHz (see Tab. 1).

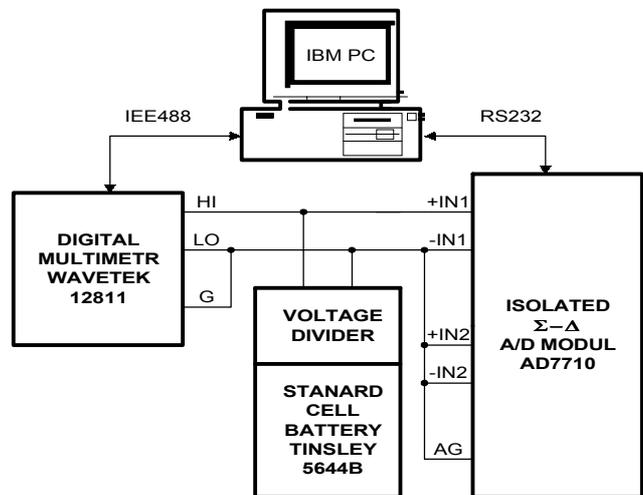


Fig. 2. Effective resolution measurement system

4. NEW APPROACH

To overcome difficulties described in Paragraph 2, new definition has been developed. It requires knowledge of amplitude distribution of the noise. The basic idea is the modification of denominator of (5) and replacement of the constant $12^{0.5}$ by other specific value, derived from the histogram by statistical uncertainty motivated approach. We are searching for the smallest interval $Noise_{pp}$ on noise probability density function characteristics that covers the

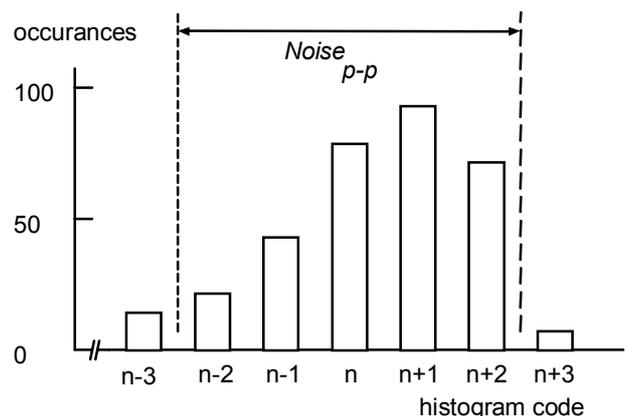


Fig. 3. Histogram evaluation

required amount of occurrences, e.g. 95% or 99%. The size of this interval is then the denominator:

$$ER_3 = \log_2 \frac{FS}{Noise_{pp}} \quad (6)$$

		EFFECTIVE RESOLUTION ER (bit)							
f_{NOTCH} [Hz]	$f_{-3\text{dB}}$ [Hz]	G = 1	G = 2	G = 4	G = 8	G = 16	G = 32	G = 64	G = 128
10	2,62	21,1	21,0	19,5	19,3	18,4	18,1	17,2	16,2
25	6,55	19,5	19,3	19,1	18,8	18,6	17,8	16,6	15,4
50	13,1	18,7	18,3	18,1	18,0	17,9	17,4	16,6	16,2
100	26,2	17,6	17,4	17,1	16,6	16,2	16,0	15,7	15,3
250	65,5	15,5	15,2	15	14,8	14,5	14,2	14	13,8
500	131	12,2	11,9	11,5	11,2	11,0	10,5	10,3	10,1
1000	262	10,3	10,1	9,9	9,7	9,5	9,3	9,1	8,9

		EFFECTIVE RESOLUTION ER ₃ (bit)							
f_{NOTCH} [Hz]	$f_{-3\text{dB}}$ [Hz]	G = 1	G = 2	G = 4	G = 8	G = 16	G = 32	G = 64	G = 128
10	2,62	19,1	19,0	17,5	17,3	16,4	16,2	15,3	14,2
25	6,55	17,6	17,3	17,2	16,8	16,5	15,8	14,6	13,4
50	13,1	16,8	16,4	16,1	16,1	15,8	15,2	14,5	14,1
100	26,2	15,5	15,4	15,2	14,5	14,1	14,1	13,6	13,4
250	65,5	13,4	13,3	13,1	12,7	12	12,3	12,4	11,7
500	131	10,3	9,8	9,5	9,4	9,2	8,8	8,2	8,0
1000	262	8,2	8,1	7,8	7,7	7,6	7,5	7,0	7,0

Tab. 1: Effective resolution measurement results for AD7710 – definitions ER and ER₃ – results for different gain and bandwidth settings

For symmetrical distributions, this algorithm leads always to single solution. For asymmetrical distributions, it is necessary to add the following artificial condition to avoid ambiguous solutions: The highest number of occurrences within the missed histogram bins should be minimal possible among all possible solutions (see Fig. 3).

For known (especially symmetrical) distributions, the value of $Noise_{pp}$ can be calculated directly from rms value of the noise by multiplication with the coverage factor k :

$$Noise_{pp} = k \cdot (RMS\ NOISE) \quad (7)$$

E.g. for normally distributed noise, one can use $k=4$ for 95% level of confidence or $k=6$ for 99% level of confidence. For uniformly distributed noise, the $k=12^{0.5}$ for 100% level confidence. For special types of distributions, the coverage factor has to be found using measured histogram case by case. An example is given in the Tab. 1. Very short example measured on successively approximating ADC of the PC plug-in board for PC is given in Tab. 2.

5. CONCLUSIONS

The general approach to definition of effective resolution of ADC was presented. The new generalised definition complies with the best of currently used definitions (5) in

applicable cases but this new definition allows to determine correctly the effective resolution in wider amount of cases (virtually there are special requirements neither for ADC input signal nor for its noise).

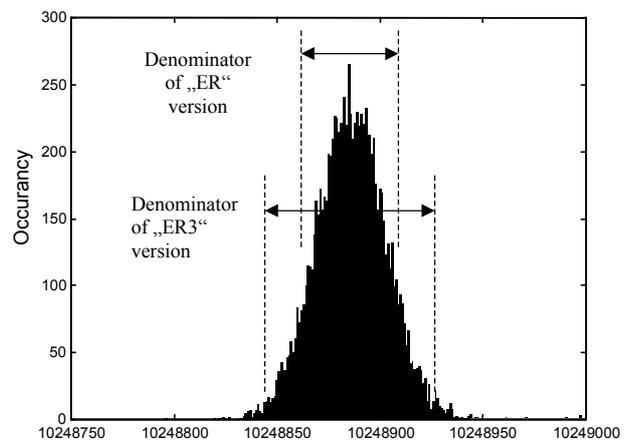


Fig. 4. Code words histogram of AD7710: $U_{IN} = 1,5272\ V$, $f_{\text{notch}} = 10\ \text{Hz}$, $G = 1$, 10^4 samples, $ER_3 = 19,1$ bits (95% confidence level, Gaussian distribution expected)

TABLE 2. Various definition of Effective Resolution - result example (12 bit ADC, 10V full scale, ideal quantisation noise 705 μ V RMS, total RMS NOISE 2,19 mV)

ER [bit]	12,16
ER_1 [bit]	10,66
ER_2 [bit]	10,36
ER_3^1 [bit]	10,36
ER_3^2 [bit]	10,16

¹ - coverage factor $12^{0,5}$ (uniformly distributed noise expected, 100% confidence level)

² - coverage factor 4 (normally distributed noise expected, 95% confidence level)

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