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Figures of Merit for Analog-to-Digital Converters: Analytic Comparison of International Standards

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Abstract *– In the paper the analytic comparison of dynamic parameters used for qualifying ADCs in the frequency domain reported in the most diffused standards is provided. This could be the first step towards their harmonization.*

Keywords *– ADC, IEC 60748, IEC 62008, IEEE Std 1241, IEEE Std 1057, DYNAD, SFDR, THD, SINAD, SNR, ENOB.*

I. INTRODUCTION

Today Analog to Digital Converters (ADCs) are used in a wide range of applications comprising data acquisition, precision industrial measurement, voice-band and audio applications [1]. Considering the thousands of converters currently on the market, selecting the proper ADC for a particular application appears to be a difficult task. Different manufacturers, in fact, specify parameters in different ways often not using the same set of specifications to describe their products. This becomes still more relevant considering that ADCs are produced and used across the world. The standardization plays an determinant role [2] in clarifying this scenario introducing common terminology and test methods that guide manufacturers in describing their products and customers in understanding converter characteristics.

However, the current situation of the standardization of measuring systems based on ADCs is characterized by the coexistence of more standards, highlighting the lack of an unified approach.

At level of official international standardization bodies, the current standard IEC 60748-97 [3] is devoted to stand-alone ADC components and only covers quasi-static operations [4]. Within the 4th Framework Programme "Standard, Measurement and Testing SMT" [5] of the European Union, the research project "Methods and draft standards for the DYNamic characterization and testing of Analog to Digital converters" (DYNAD) was proposed and successfully financed [6]. The project aimed at integrating and complementing IEC Standard [3] for the part concerning dynamic testing, by proposing a list of parameters specifying the dynamic behavior of the converter or sample & hold, and indicating in detail the measurement conditions and the data processing algorithms to be adopted. Also this project seems to be mainly devoted to characterization of the ADC as a standalone component, rather than to a complex digital measuring system including relevant hardware and software [2].

At level of category standardization, a remarkable effort has been done by the Technical Committee 10 of the IEEE Instrumentation and Measurement Society through the IEEE 1057-94 [7] and IEEE 1241-00 [8] standards. The former has the great value of making a punctual state of the art by focusing metrological performance specifications and testing procedures in an unambiguous way. However, it is specifically devoted to waveform recorders rather than to general digital measuring systems [2]. The latter provides both standard terminology for specifying the performance of ADCs and test methods for measuring it [2]. It has many similarities to IEEE Std. 1057, many of the terms and tests are nearly the same, since ADCs are a necessary part of digitizing waveform recorders [2].

Very recently the IEC Standard 62008 [9] on the "Performance characteristics and calibration methods for digital data acquisition systems and relevant software" has been released. This standard is aimed to ensure that all measurement systems that rely on Data AcQuisition (DAQ) devices meet a common standard. This standard covers the minimum specifications that the DAQ device manufacturer must provide to describe the performance of the Analogue-to-Digital Module (ADM) of the DAQ device, standard test strategies to verify the minimum set of specifications, the minimum calibration information, required by the ADM, that is stored on the DAQ device and the minimum calibration software requirements for external and self-calibration of the ADM of the DAQ device [9].

This paper is aimed at providing an analytic comparison of parameters used for qualifying ADCs reported in the most diffused standards that can be used at an international level to put in evidence similarities and/or possible ambiguities and lacks in the parameter definitions and descriptions. This could be the first step towards the realization of a unique ADC standard by joining and harmonizing the existing ones. The paper describes the first results of this work considering the most widely used ADC dynamic parameters in the frequency domain: Spurious Free Dynamic Range (SFDR), Total Harmonic Distortion (THD), SIgnal to Noise And Distortion ratio (SINAD), Signal to Noise Ratio (SNR) and Effective Number Of Bits (ENOB).

This work analyses the ADC dynamic parameters included in the standards produced by official international standardization bodies, IEC 60748-4 and IEC 62008, and also those belonged to category standardization, IEEE Std. 1057 and IEEE Std. 1241, as they have a very diffused usage across the world. As quoted above IEC 60748-4 only covers static parameters therefore, while waiting for the release of the new IEC 60748-4-X including dynamic criteria for ADC, it has been chosen to consider the DYNAD definitions as its purpose is to fill the part of IEC Standard concerning dynamic testing. At the time this paper was written IEC 62008 was not been acquired yet, this is the reason of using the Draft version [10] of this standard in the following as reference. IEEE TC-10 is currently engaged in the revision of IEEE Std. 1057-1994 and IEEE Std. 1241-2000, the analysis reported in this paper is referred to the released versions.

The paper has been divided in five sections, each of them analyzes a single parameter according to the considered standards including: i) its definitions with the formulas, ii) its description, and iii) connected formulas including relations with other parameters or alternate forms of the definition formula and comments.

II. SPURIOUS FREE DYNAMIC RANGE

An ideal ADC, receiving as input a pure sinewave, provides at the output a sampled sinewave. Actual ADCs are on the contrary characterized by outputs including spurious signals within the device. These signals generally are combination of the harmonics of the fundamental and intermodulation products, but they can be also caused by non-harmonic persistent frequency components. ADC standards make a distinction between the spurious tones [6] or components [7,8] and the harmonic distortion [6,7,8] meaning the first ones "*persistent sine wave at frequency other than the harmonic frequencies*" [7,8], reference [6] also adding "*or intermodulation frequencies*". The harmonic distortion, instead, is defined as "*output components at frequencies that are an integer multiple of the applied sine wave frequency which are induced by the input sine wave*", for a pure sine wave input [6,7,8]. Both spurious components and harmonic distortion degrade the range of ADC input signal levels that can be reliably measured simultaneously, in particular the ability to accurately measure small signals in the presence of large ones. SFDR is used as a measure of this degradation.

IEEE Std. 1057 and IEC 60748 don't include any SFDR parameter definition for characterizing the ADC dynamic range, even though its wide use. On the contrary, IEEE Std. 1241 defines SFDR as "*the ratio of the amplitude of the ADC output averaged spectral component at the input frequency, f_i, to the amplitude of the largest harmonic or spurious spectral component observed over the full Nyquist band"* for a pure sine wave input of specified amplitude and frequency. The formula is reported in Tab.I.

According to DYNAD, SFDR "*expresses the range, in dB, of input signals lying between the averaged amplitude of the ADC's output fundamental tone, f_i, to the averaged amplitude of the highest frequency harmonic or spurious spectral component observed over the full Nyquist band*". The formula of SFDR for a pure sine wave input of specified amplitude and frequency is also reported in Tab.I.

The IEEE Sdt. 1241 definition uses the word "*ratio*", while DYNAD adopts the word "*range*" making immediately understandable what is represented by SFDR on an amplitude spectrum. In the test method section of IEEE Std. 1241, SFDR is specified as the ratio is between amplitudes of averaged DFT values. Moreover, the IEEE Sdt. 1241 highlights that SFDR is generally a function of the amplitude and the frequency of the input sine wave, as well as possibly, of the ADC sampling frequency and input noise or dither.

In the section devoted to the calculation of the dynamic parameters in the frequency domain, DYNAD reports SFDR formula in terms of averaged power spectrum. The quoted above SFDR formulas reported by [6,8] apply when an integer number of periods of the sampled waveform are acquired, that is the coherent sampling condition. DYNAD takes into account also the case of non-coherent sampling conditions, when the ratio between the input frequency, f_i, and the sampling frequency, f_s, is not an integer value, considering the relationship between f_i and f_s as:

$$f_i = \left(J \pm \varepsilon_j\right)\frac{f_s}{M} \tag{1}$$

where J is an integer number of cycles of the input waveform, so that the periodic extension of the sample set is continuous and ε_j is the number of cycles inaccuracy ($\varepsilon_j \leq 0.5$, $\varepsilon_j=0$ in case of coherent sampling). DFT is performed on an M sample long record. To take in account the effect of the windowing, the FFT amplitude at the frequency bin J is multiplied by the factor:

$$\frac{\left|W[0]\right|}{\left|W_c\left(\dfrac{\varepsilon_j f_s}{M}\right)\right|} \tag{2}$$

where $W[0]$ and $W_c(\varepsilon_j f_s/M)$ are reported in Tab.I. As it can be seen from Tab.1 the two SFDR formulas provided by [6] in case of coherent and non-coherent sampling are equal except for the additive correction term in case of non-coherent sampling. Moreover, except for a notation difference, they are equal to the definition found in [8].

The approach followed by the IEC 62008 draft to define SFDR needs a separate discussion, since it is different from those adopted by the other standards. SFDR is "*for a pure sinewave input, ratio, expressed in dB, of the rms value of the output at any other single frequency except for harmonic components of input signal. This parameter is dependent on the frequency of input signal and is expressed in dB*". In the unique reported formula to calculate this parameter, (Tab.I), the rms value of the output signal is "*determined from the amplitude of the ADM output at the input signal frequency*", the rms value of the largest single other component is instead "*the rms value of the largest component excluding the DC term, the fundamental, and the harmonic components of the input signal*".

Therefore, harmonics are not considered as spurious signals and consequently they are not included in the SFDR definition and computation. Although in the DAQ systems the harmonic distortion is not a relevant parameter, applications where good SFDR is important don't really care whether the spur is a harmonic or not, but which range is free from distortions.

III. TOTAL HARMONIC DISTORTION

THD is another parameter to measure the harmonic distortion caused by ADC nonlinearity that takes into account the amplitude of the harmonics of the fundamental signal.

IEC 69748 and IEC 62008 draft standard don't include THD parameter definition. IEEE Std. 1241 in the terminology section states that THD is "*for a pure sine wave input of specified amplitude and frequency, the root-sum-of-squares (rss) of all the harmonic distortion components including their aliases in the spectral output of the ADC. Unless otherwise specified, THD is estimated by the rss of the second through the tenth harmonics, inclusive. THD is often expressed as a decibel ratio with respect to the root-mean-square amplitude of the output component at the input frequency*".

In DYNAD THD is "*the ratio of the rss (root-sum-of-squares) of all the harmonic distortion components, including their aliases in the spectral output of the ADC, to the rms amplitude of the output fundamental component, expressed in dB. The input stimulus is assumed to be a high purity sine wave. Unless otherwise specified, THD is estimated considering the second through the tenth harmonics, inclusive*". DYNAD uses the term *ratio* in the definition while [8] states that THD is often expressed as a ratio, except for this the two definitions are the same.

The IEEE Std. 1241 THD formula (Tab.II) is the rss of a specified set of harmonic distortion components (h) including their aliases. Alternate THD% and THD_{dB} formulas are included in the standard, too.

DYNAD reports also THD expressed in term of power in the cases of coherent and non-coherent sampling including terms taking in account the windowing effect in the second case (Tab.II). In order to minimize errors in the measurements of THD, SINAD and SFDR, DYNAD states that "*the harmonic distortion of the input sinewave must be less than the THD of the ADC under test*". Therefore, DYNAD adds a guideline for the THD measurement in the worst case, when the THD of the ADC under test and the input sinewave distortion are dominated by the same harmonic component (same frequency and same phase) and in all the other cases, when the THD of the ADC as well as the distortion of the input sinewave result from a distortion over many harmonic components having not necessary the same frequency and/or the same phase.

IV. SIGNAL TO NOISE AND DISTORTION RATIO AND SIGNAL TO NOISE RATIO

Any deviation between the ADC output signal (converted to input units) and the input signal not including (i) deviations caused by linear time invariant response of the system, (ii) harmonics of the fundamental up to a prefixed order, or (iii) a DC level shift is commonly attributed to noise [6,7,8,10]. Noise is caused by phenomena acting on either phase or amplitude of the input signal like, for example, the effects of random errors (random noise), fixed-pattern errors, high order harmonics or intermodulation distortion and aperture uncertainty [5,6,8].

IEC 62008 draft standard adds that "*for DC or very low frequency input signals it is usual to describe system noise which does not include the effect of non-linearity and time base errors*" and that "*SINAD and ENOB include the effects of non-linearity and time base errors*".

ADC noise performances are dealt with in different ways by the standards [6,7,8,10], using different terms depending on the considered output noise includes or not harmonic distortion. IEEE Std. 1057 defines the amount of noise present in the output using SNR, "*the ratio of root mean square (rms) signal to rms noise for sine wave input signals. The SNR depends on the amplitude and frequency of the applied sine wave. The amplitude and frequency at which the measurement was made shall be specified*".

IEEE Std. 1241, instead, uses SINAD, which is defined in the same manner as SNR one in [7]. The term SNR is not used in [8] because, in the context of ADC testing, it is used in different ways being too ambiguous. SINAD stated in [8] is defined as "f*or a pure sine wave input of specified amplitude and frequency, the ratio of the rms amplitude of the ADC output signal to the rms amplitude of the output noise, where noise is defined to include not only random errors but also nonlinear distortion and the effects of sampling time errors*". The formulas are reported in Tab.III. The IEEE Std. 1241 reports also the formula to calculate this parameter in the frequency domain (Tab.III). Moreover, it introduces another parameter, the Signal to Non-Harmonic Ratio (SNHR), defined for a pure sine-wave input of specified amplitude and frequency, as "*the ratio of the rms amplitude of the ADC output signal to the rms amplitude of the output noise which is not harmonic distortion*". As it can be seen, the use of SINAD and SNHR couple instead of SNR clarifies whether the test result includes the harmonic distortion or not.

However, because of its utility in a variety of ADC applications and comparative purposes, IEEE Std. 1241 reports a *normalized SNR* measure. It is normally obtained from the ratio of the signal to the portion of noise that is not harmonic distortion, as for the SNHR, using a sinusoidal test signal.

DYNAD defines both SNR and SINAD. The former is "*a measure of the broadband noise and spurious that are introduced into the ADC output signal by the sampling and AD conversion processes. It is given by the ratio, expressed in dB, of the signal power to noise (including spurious) power, i.e., of the rms amplitude of the ADC output fundamental tone to the rms amplitude of the spectral content defined by the sum of all frequencies in the Nyquist band ($f_s/2$) excluding DC, fundamental, and harmonics*". This corresponds to the SNHR definition in [8]. The latter is "*for a pure sinewave input of specified amplitude and frequency, the ratio of the rms amplitude of the ADC output fundamental tone to the rms amplitude of the output noise, where noise is defined as to include not only random errors but also non-linear distortion and the effects of sampling time errors, i.e.,*

Table I. SFDR formulas.

IEEE Std 1241	$SFDR(dB)=20\log_{10}\left(\dfrac{\lvert X_{avg}(f_i)\rvert}{\max_{f_S,f_h}\{\lvert X_{avg}(f_h)\rvert or \lvert X_{avg}(f_S)\rvert\}}\right)$	X_{avg}: averaged spectrum of the ADC output; f_r: input signal frequency; f_h and f_s: frequencies of the set of harmonic and spurious spectral components.
DYNAD coherent sampling	$SFDR(dB)=20\log\left(\dfrac{\lvert Y_{avm}(f_i)\rvert}{\max_{f_{sp},f_h}\{\lvert Y_{avm}(f_h)\rvert,\lvert Y_{avm}(f_{sp})\rvert\}}\right)$	Y_{avm}: average of an adequate number of amplitude spectra, corresponding to different data records collected at the ADC output; f_i: input signal frequency; f_h and f_{sp}: frequencies of the set of harmonic and spurious spectral components.
DYNAD non-coherent sampling	$SFDR_{dB}=10\log\left(\dfrac{\lvert Y_{avm}[J]\rvert^2}{\max_{f_h,f_{sp}}\{\lvert Y_{avm}[f_h]\rvert^2,\lvert Y_{avm}[f_{sp}]\rvert^2\}}\right)+$ $+10\log\left(\dfrac{\lvert W[0]\rvert^2}{\left\lvert W_C\left(\dfrac{\varepsilon_{jr}f_S}{M}\right)\right\rvert^2}\right)$	ε_{jr}: number of cycles inaccuracy rounded to one decimal; J: integer; $W[0]=\sum_{n=0}^{M-1}w[n]$ w[n]: window function coefficient for a DFT; $W_C\left(\dfrac{\varepsilon_j f_S}{M}\right)=\int_{-\infty}^{+\infty}e^{-i2\pi\frac{\varepsilon_j f_S}{M}}w(t)dt$ M: number of samples.
IEC Std draft 62008	$SFDR=20\log_{10}\left(\dfrac{\text{rms value of output signal}}{\text{rms value of largest single other component}}\right)$	

Table II. THD formulas.

IEEE Std 1241	$THD=\dfrac{1}{M}\sqrt{\sum_h (X_{avm}(f_h))^2}$	$X_{avm}(f_h)$: averaged magnitude of the component at the hth harmonic of the DFT of the ADC output data record M: number of samples in the data record.
DYNAD coherent sampling	$THD_{dB}=10\log\left(\dfrac{\sum_{h=2}^{h_{max}}\lvert Y[hJ]\rvert^2}{\lvert Y[J]\rvert^2}\right)$	Y[hJ]: h^{th} harmonic component.
DYNAD non-coherent sampling	$THD_{dB}=10\log\left(\dfrac{\sum_{h=2}^{h_{max}}\lvert Y[hJ]\rvert^2\dfrac{\lvert W[0]\rvert^2}{\left\lvert W_C\left(\dfrac{frac_r\lvert h(J\pm\varepsilon_j)\rvert f_S}{M}\right)\right\rvert^2}}{\lvert Y[J]\rvert^2\dfrac{\lvert W[0]\rvert^2}{\left\lvert W_C\left(\dfrac{\varepsilon_{jr}f_S}{M}\right)\right\rvert^2}}\right)$ $=10\log\left(\dfrac{\sum_{h=2}^{h_{max}}\dfrac{\lvert Y[hJ]\rvert^2}{\left\lvert W_C\left(\dfrac{frac_r\lvert h(J\pm\varepsilon_j)\rvert f_S}{M}\right)\right\rvert^2}}{\lvert Y[J]\rvert^2}\left\lvert W_C\left(\dfrac{\varepsilon_{jr}f_S}{M}\right)\right\rvert^2\right)$	$frac_r[x]$: fractional part of x rounded to the first decimal.

Table III. SINAD and SNR formulas.

IEEE Std 1241	$SINAD = \frac{\text{rms signal}}{\text{rms noise}}$ Equivalent to SNR in IEEE Std 1057 $\text{rms noise} = \frac{1}{M}\sqrt{\sum_{m=0}^{M-1} E_{avm}(f_m)^2}$ Frequency domain calculation	E_{avm}: residual spectrum of X_{avm} $X_{avm}(f_m)$ the averaged magnitude spectral component at discrete frequency f_m after a DFT
DYNAD coherent sampling	$SINAD_{dB} = 10\log\left(\frac{\|Y[J]\|^2 - \|NFl\|^2}{\sum_{k=1,k\neq J}^{M/2-1}\|Y[k]\|^2 + 2\|NFl\|^2 + \frac{1}{2}\left\|Y\left[\frac{M}{2}\right]\right\|^2}\right)$ $\|NFl\|^2 = \frac{\sum_{k=1,k\neq J,k\neq hJ}^{M/2-1}\|Y[k]\|^2 + \frac{1}{2}\left\|Y\left[\frac{M}{2}\right]\right\|^2}{\frac{M}{2} - h_{\max}}$	h_{max}: the highest harmonic to remove. $h = 2 \ldots h_{\max}$
DYNAD non-coherent sampling	$SNR_{dB} = 10\log\left(\frac{\|Y[J]\|^2 - \|NFl\|^2}{\sum_{k=1,k\neq J,k\neq hJ}^{M/2-1}\|Y[k]\|^2 + (h_{\max}+1)\|NFl\|^2 + \frac{1}{2}\left\|Y\left[\frac{M}{2}\right]\right\|^2}\right)$ $\|NFl\|^2 = \frac{\sum_{k=1,k\neq J\pm 1,k\neq rnd\left[h(J\pm\varepsilon_j)\right]\pm l}^{M/2-1}\|Y[k]\|^2 + \frac{1}{2}\left\|Y\left[\frac{M}{2}\right]\right\|^2}{\frac{M}{2} - h_{\max}(2l_{\max}+1)}$	rnd[x]: round to the nearest integer of x, Y[hJ]: h^{th} harmonic component, $2l_{max}$: number of bins to remove around the signal and its harmonics. $l = 0 \ldots l_{\max}$
IEC Std draft 62008	$SINAD = 20\log_{10}\left(\frac{\text{rms value of output signal}}{\text{rms value of noise}}\right)$	

the sum of all non-fundamental spectral components in the range from DC (excluded) up to half the sampling frequency ($f_S/2$)". This definition corresponds to SINAD definition reported in IEEE Std. 1241. The formulas reported in [6] and in Tab.III, comprise the SINAD and SNR in the frequency domain in case of coherent and non-coherent sampling. Two chapters are devoted to their time-domain measurement, too. Another chapter of [6] deals with SINAD calculation in the dual tone test. Concerning the SNR and/or SINAD relations with other parameters, [8] reports a formula relating SINAD with ENOB, while [7] reports the same relation for SNR.

IEC 62008 draft standard defines SINAD as "*for a pure sinewave input, ratio of the rms amplitude of the ADM output signal at the input frequency to the rms amplitude of all other signal in the ADM output*", in a note is also suggested that "*SINAD information should be supplied at a range of gains over a range of input and sampling frequencies*". In the SINAD formula, reported in Tab.III, the rms value of output signal is the same appearing in the SFDR formula, while the rms value of noise that includes harmonics is "*determined by the root of the sum of squares of all of the terms of the output, excluding the DC term and input frequency*". This definition is the same of those reported by IEEE Std. 1241 and DYNAD, but in this case the term SNHR doesn't appear in the standard, meaning that the noise is always considered to include the harmonic distortion for this parameter. Considering that IEC 62008 draft standard doesn't include a THD definition, information about the harmonic distortion content are taken into account only in the SINAD parameter. In fact, simply inverting SINAD formula a figure of merit referred to as THD+N can be obtained [11].

V. EFFECTIVE NUMBER OF BITS

Excessive noise in an ADC can make it appear to have fewer bits of resolution than it actually has. The apparent resolution of an ADC is specified by the ENOB.

IEEE Std. 1057 and IEC 69748 don't include ENOB definition. IEEE Std. 1241 defines ENOB as "*a measure of the signal-to-noise and distortion ratio used to compare actual ADC performance to an ideal ADC*". A formula for an input sine wave of specified frequency and amplitude, after gain and offset correction (equal to the one reported in [7]) is also provided (Tab.4). To take into account the effect of jitter on ENOB, [8] states other two formulas. The relation between SINAD and ENOB is also reported (Tab.4). DYNAD defines ENOB (N_{ef}) as the number that "*in practice identifies the actual resolution of the converter taking into account the signal to noise and distortion ratio*" adding that it can be interpreted as it follows: "*if the actual noise is attributed only to the quantisation process, the ADC under test can be considered as equivalent to an ideal N_{ef} -bit ADC insofar as they produce the same rms noise level*". The ENOB formula and the relation with SINAD according to [6] are reported in Tab.IV. Moreover, DYNAD advices to avoid this parameter, since the same information is contained in the SINAD measured when applying a full-scale sine wave at the input of the ADC. In [6] there is a chapter devoted to the time domain measurement of N_{ef} and another one concerning its calculation in the dual tone test.

IEC 62008 draft standard defines ENOB stating "practical limit of the resolution of an ADM due to inherent noise and linearity error. Effective number of bits represents that the ADM performs as an ideal ADM with this number of bits". In a note is also suggested that "Effective number of bits information should be supplied at a range of gains over a range of input and sampling frequencies". ENOB is calculated directly from SINAD as reported in Tab.IV.

VI. CONCLUSIONS

The analytic comparison of the most used ADC parameters according to the most diffused standards could be the first step towards the realization of a unique ADC standard. The paper analyzes SFDR, THD, SINAD, SNR and ENOB to put in evidence similarities and/or possible ambiguities and lacks in the parameter definitions and descriptions taken from IEC 62008 draft standard, IEEE Std. 1057, IEEE Std. 1241 and DYNAD. Future developments of this work will concern the analysis of other ADC parameters as well as those included in this paper taking into account the released IEC 62008 and the new IEC 60748-X as soon as it will be released.

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Table IV. ENOB formulas.

IEEE Std 1241	$ENOB = N - log_2\left(\dfrac{rms\ noise}{ideal\ rms\ quantization\ error}\right) = log_2\left(\dfrac{full\ scale\ range}{rms\ noise \cdot \sqrt{12}}\right)$	N: number of digitized bits
ENOB vs SINAD	$ENOB = \log_2(SINAD) - \dfrac{1}{2}\log_2(1.5) - \log_2\left(\dfrac{A}{(V/2)}\right)$	A: amplitude of the sine wave fitted to the output V: full-scale range of the ADC under test.
DYNAD	$N_{ef} = N - \log_2 \dfrac{\eta_{rms}}{\sigma_{eq}}$	η_{rms} : *rms* total noise including jitter and harmonic distortion σ_{eq} : ideal *rms* quantisation noise for a sinusoidal input.
ENOB vs SINAD	$N_{ef} = \dfrac{SINAD_{dBFS} - 1.76dB}{6.02}$ $\qquad SINAD_{dBFS} = SINAD_{dB} - 20\log(SFSR)$	SFSR: for a pure sinewave input of specified amplitude and frequency, the ratio of the ADC's output fundamental tone to the amplitude of a full scale sinewave at the same frequency.
IEC Std draft 62008	$ENOB = (\text{signal to noise and distortion ratio - 1.76})/\,6.02$	