World Journal of Advanced Engineering Technology and Sciences

eISSN: 2582-8266

Cross Ref DOI: 10.30574/wjaets

Journal homepage: https://wjaets.com/

(Research Article)

Check for updates

On the applications of sinusoidal signals in analog-to-digital converter testing

Francisco André Corrêa Alegria *

Instituto de Telecomunicações and Instituto Superior Técnico, Technical University of Lisbon, Portugal.

World Journal of Advanced Engineering Technology and Sciences, 2023, 10(02), 058–067

Publication history: Received on 11 October 2023; revised on 20 November 2023; accepted on 23 November 2023

Article DOI: https://doi.org/10.30574/wjaets.2023.10.2.0292

Abstract

Analog-to-Digital converters are an essential component of modern electronics systems, especially those that interface with the real world through sensors and actuators. Their testing is thus paramount in evaluating the performance of those systems. That evaluation is carried out most often using sinusoidal stimulus signals. After a brief overview of applications where sinusoidal signals play a vital role, we focus on their use when characterizing analog-to-digital converters using different test methods that aim at estimating several metrological characteristics like frequency response, signal-to-noise ratio, linearity, harmonic distortion, and spurious free dynamic range.

Keywords: Sinusoidal; Analog-to-Digital Converter; Characterization; Testing; Stimulus Signal.

1. Introduction

Here we focus on the use of sinusoidal signals do characterize analog-to digital converters (ADCs). These are very important because a periodic signal with an arbitrary shape can be mathematically described by a discrete sum of sine waves through the discrete Fourier Transform. In linear systems, the output will be the sum of the responses one gets with a single sinusoid at the input at one time. Focusing the study on sinusoidal stimulus signals is not so restrictive as one might think initially.

We will begin with a brief introduction regarding the mathematical description of a sinusoidal signal, its parameters and present a figure with an example signal, for context. This type of signal is what is typically used as stimulus signal. Naturally, in different applications, we will have measured signals that will be distorted versions of this signal. Those distortions is what is important to be quantifies in order to characterize those systems.

After that, we overview briefly several applications where sinusoidal signals are used to present an idea of the generality of this study, before going, in the next section, into the different metrological characteristics of ADCs [1]-[2] and how they are determined using sinusoidal signals.

Sinusoidal signals are periodic signals characterized by their amplitude (A), frequency (f), initial phase (φ) and sometimes their average value or offset (C). Mathematically their commonly written as

$$x(t) = C + A \cdot \cos(2\pi f \cdot t + \varphi), \quad (1)$$

where, sometimes, the frequency is expressed as an angular frequency, ω, such that

$$\omega = 2\pi f. \quad (2)$$

The period of the signal is, be definition, the inverse of the frequency, thus

* Corresponding author: Francisco André Corrêa Alegria; Email: falegria@lx.it.pt

$$T = \frac{1}{f}. \quad (3)$$

Figure 1 shows an example of one period of a sinusoidal signal with unit amplitude (in arbitrary units), no offset, null initial phase and a frequency of 10 Hz (period of 100 ms).

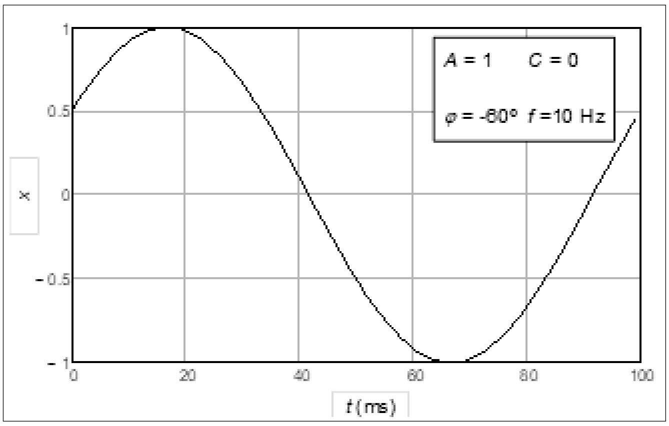

Figure 1 Example of a sinusoidal signal with unit amplitude in arbitrary units, null offset, 10 Hz of frequency and an initial phase of -60º.

Sinusoidal signals, which are characterized by their sine or cosine waveforms, have a wide range of applications across various fields due to their periodic and repetitive nature. In electrical engineering they are used to transmit a distribute energy from the power plants to homes and factories [3]. In signal processing they constitute a canonical signal it which other signals may be decomposed using Fourier analysis [4]. This allows for the study of signal filtering, amplification, and modulation. In mechanical engineering they can be used in vibration analysis [5] in mechanical systems, or as sound waves for the transmission of data using modulation. Also, in metrological applications like measuring distance [6]-[7], water flow velocity [8]-[10] or defects in conductive materials using eddy currents [11], they are usually the signal shape of choice. In physics these are shapes encountered in pendular motion [12] or in spring-mass systems [13] and are also used to describe various wave phenomena, like electromagnetic waves and water waves. In telecommunications they can be used as radio waves used in wireless communication [14], for example, where they are often modulated in amplitude, frequency or phase which involve manipulation these parameters of the carrier to transmit information. Sinusoidal signals are also used in control systems, like PID controllers [15], that is, proportional-integral-derivative controllers that use sinusoidal signals to control various processes and systems. Also, in music and audio we have musical notes can be represented as sinusoidal signals with different frequencies and amplitudes and in sound synthesis we have oscillators are used in synthesizers [16]. In medical imaging, like magnetic imaging resonance (MRI), use sinusoidal radiofrequency (RF) signals to excite and then detect signals from the body's tissues [17]. In seismology, seismic waves generated by earthquakes and other geological events can be modeled as sinusoidal signals [18]. In navigation we have the global positioning system (GPS) where the receivers use signals from satellites, which are modulated using sinusoidal carrier waves, to determine precise locations [19]. Finally, in optics we have the behavior of light, including diffraction and interference, which can be described using sinusoidal waveforms [20].

These examples illustrate the versatility and importance of sinusoidal signals in understanding and manipulating natural phenomena and engineering systems across different disciplines. There are many more examples where the measurement of physical quantities is of interest and can be achieved by different methods [21]. In the following we are going to focus on the use of sinusoidal signals for the characterization of analog-to-digital converters (ADCs).

In frequency response testing, for example, a sinusoidal signal generator is used to produce sinusoidal input signals at different frequencies. These signals are fed into the ADC, and the resulting digital output is analyzed. The goal is to determine the ADC's gain and phase response across the frequency spectrum. Engineers use this data to ensure that the ADC performs accurately across its specified bandwidth.

In signal-to-noise ratio (SNR) measurement a sinusoidal signal with a known amplitude and frequency is applied as input to the ADC. Its output is analyzed to measure the amplitude of the signal and the level of noise present. SNR is calculated as the ratio of the signal's amplitude to the noise level, often expressed in decibels (dB). A high SNR indicates good performance, as it means the signal is well-distinguished from noise.

In total harmonic distortion (THD) analysis sinusoidal signals with a known amplitude and frequency are used as input signals. The ADC's output signal is analyzed to identify and quantify harmonic distortion components. THD is expressed as a percentage and represents the ratio of the sum of the amplitudes of the harmonics to the amplitude of the fundamental frequency.

In intermodulation distortion (IMD) testing two or more sinusoidal signals at different frequencies are simultaneously applied to the ADC. IMD testing reveals how the ADC responds to the nonlinear mixing of these signals. The resulting output signal is analyzed to detect and quantify intermodulation distortion products.

In linearity testing sinusoidal signals with varying amplitudes are used as input signals [22]-[23]. The ADC's output is compared to the expected linear response. Deviations from linearity are measured to assess the ADC's accuracy in converting signals of different amplitudes.

In sensitivity analysis sinusoidal signals with small, controlled amplitude variations are applied as input. Engineers examine how the ADC responds to these small changes. This analysis helps determine the minimum detectable input signal change, which is important in applications requiring high sensitivity.

In dynamic range measurement a sinusoidal signal with gradually increasing amplitude is applied to the ADC. The ADC's output is monitored as the input amplitude increases. The dynamic range is defined as the range of input amplitudes over which the ADC provides an accurate output.

In spurious-free dynamic range (SFDR) measurement sinusoidal signals are applied as input signals, often with varying frequencies and amplitudes. Engineers measure the peak amplitude of the largest undesired spurious component in the output. SFDR quantifies how well the ADC can suppress unwanted spurious signals.

Sinusoidal signals of varying frequencies and amplitudes are used as input to carry out harmonic analysis where the ADC's output signal is analyzed to identify and quantify harmonic distortion components, which are multiples of the input frequency.

In audio applications, sinusoidal signals of known frequencies and amplitudes are used to calibrate and test audio ADCs, amplifiers, and speakers. This ensures that audio equipment accurately reproduces sound without distortion.

Sinusoidal signals are used as carrier waves in communication systems, such as AM and FM radio. ADCs are employed in receivers to digitize these signals for demodulation and further processing and also in radar and sonar systems as part of the transmitted signal. ADCs digitize the received echoes, allowing for the detection and analysis of distant objects.

These examples illustrate how sinusoidal signals play a crucial role in characterizing ADCs [24]-[25]. We will now delve into some specifications used to quantify the performance of ADCs and which use sinusoidal signals.

2. Frequency Response

Frequency response testing is a critical procedure used to characterize the performance of analog-to-digital converters (ADCs) and other electronic systems with respect to their ability to handle signals across a range of frequencies. The primary goal of frequency response testing is to understand how a device responds to signals of different frequencies within its operational bandwidth. It assesses whether the device accurately reproduces the amplitude and phase of input signals across various frequencies.

A sinusoidal signal generator is used to produce a series of sinusoidal input signals at different frequencies. The frequencies chosen for testing are typically within the specified bandwidth of the device being evaluated. The amplitude of the input signal is often kept constant during testing.

Measurements are taken at various points in the device's signal path to assess its response. For ADCs, this includes the input, output, and internal nodes if necessary. The input and output signals are usually compared to determine how accurately the device processes the input signal.

Gain represents the ratio of the output signal's amplitude to the input signal's amplitude at each tested frequency point. It quantifies the device's signal amplification or attenuation at different frequencies. Phase represents the phase shift introduced by the device at each frequency point. It quantifies the time delay or phase distortion.

Frequency response testing involves sweeping the input signal frequency continuously or stepping through discrete frequency points. A continuous sweep provides a complete picture of the device's response across its entire bandwidth.

Frequency response testing can be used to determine the device's bandwidth, which is the range of frequencies over which the device operates effectively. The bandwidth is often defined as the frequency range within which the gain is within a specified tolerance of its maximum value, usually -3 dB which represents half the signal power.

Phase margin is a parameter used to evaluate the stability of feedback systems. It quantifies how close the system is to instability. Group delay measures the time delay introduced by the device as a function of frequency. It is important in applications where signal timing is critical.

Frequency response testing is crucial in various applications, including audio equipment design, RF (radio frequency) and microwave circuit design, control systems, and communication systems. It ensures that devices accurately process signals over a wide range of frequencies, which is essential for their intended functions. It can be challenging due to the need for precise signal generation and measurement equipment. Accurate calibration and compensation for measurement system characteristics are often required to obtain reliable results.

In summary, frequency response testing is a comprehensive evaluation method that assesses how a device performs across a range of frequencies. It is crucial in ensuring that ADCs and other electronic systems operate as intended and provide accurate signal processing capabilities across their specified bandwidths.

3. Signal-to-Noise Ratio Measurement

Signal-to-Noise Ratio (SNR) measurement is a fundamental technique used to assess the quality of signals processed by analog-to-digital converters (ADCs) and other electronic systems. It quantifies the ratio of the desired signal (the "signal") to unwanted background noise (the "noise") [26]. The primary purpose of SNR measurement is to determine how well a system or device can distinguish the desired signal from background noise. SNR is a critical parameter in various applications, including audio processing, communications, image processing, and scientific measurements.

The "signal" represents the amplitude of the useful or desired input signal. It's the component of the input that carries the information of interest. The "noise" includes any unwanted or random variations in the signal that can obscure or degrade the information. Noise can be electrical, thermal, or environmental in nature. It can also be additive in nature, like voltage noise, that is added to the other signals or can take the for of phase noise on the oscillator creating the sinusoidal signals [27] or even jitter in the sampling instant on data acquisition systems [28].

To measure SNR, a known and consistent signal is applied to the input of the system or device under test. This signal should be representative of the typical signals the system will encounter in practice. The system's output is captured and analyzed to determine both the signal amplitude and the noise level.

SNR is typically expressed in decibels (dB), which is a logarithmic unit. The formula for calculating SNR in dB is

$$SNR = 10 \cdot \log_{10}\left(\frac{signal\ power}{noise\ power}\right). \quad (4)$$

Signal power and noise power are usually calculated as the squared magnitude (amplitudes) of the signal and noise components.

Measuring SNR accurately can be challenging, especially when dealing with very low-level signals or high levels of noise. Noise can come from various sources, including thermal noise, quantization noise (in ADCs), electromagnetic interference, and more. Identifying and isolating the relevant noise sources is critical. In audio applications, SNR measurement assesses how well an audio system can reproduce the desired sound compared to the background noise. In communication systems, SNR affects the quality of received signals, determining how accurately data can be recovered. In image processing, SNR is crucial for assessing image quality, especially in medical imaging and surveillance. In scientific measurements, SNR is used to evaluate the precision and accuracy of instruments and sensors.

In the context of ADCs, the bit depth (number of bits) of the ADC plays a crucial role in determining the achievable SNR. ADCs with higher bit depths can represent smaller signal levels and noise variations, leading to better SNR.

SNR is related to the dynamic range of a system, which is the range between the smallest and largest input levels it can handle while maintaining acceptable SNR. Dynamic range is often expressed in dB and is closely tied to SNR. In real-time systems, SNR measurement may be done continuously to monitor the quality of incoming signals and adapt processing parameters accordingly.

Precise calibration of measurement equipment and careful consideration of measurement conditions are essential to obtaining accurate SNR measurements. In summary, SNR measurement is a critical evaluation method that quantifies the ratio of the desired signal to unwanted noise. It is essential for assessing the quality and performance of ADCs and other electronic systems in a wide range of applications, ensuring that the signals of interest can be reliably extracted from background noise.

4. Total Harmonic Distortion

Total Harmonic Distortion (THD) analysis is a technique used to assess the level of harmonic distortion present in the output signal of an electronic device, particularly analog-to-digital converters and audio equipment. Harmonic distortion occurs when a device introduces unwanted frequency components (harmonics) that are multiples of the input signal's frequency.

The primary purpose of THD analysis is to quantify how much the output signal deviates from the ideal, pure sinusoidal input. It provides a measure of the distortion introduced by the device, which can affect the quality of audio, video, and other signal processing applications. In THD analysis, a pure sinusoidal signal with a known frequency and amplitude is generated and applied as the input to the device under test (DUT). The frequency of this test signal is usually chosen to be within the operational bandwidth of the DUT. The output signal from the DUT is captured and analyzed using a spectrum analyzer or similar equipment. The spectrum analyzer breaks down the output signal into its constituent frequency components, including the fundamental frequency (the input signal) and harmonic frequencies.

THD is calculated as the ratio of the root mean square (RMS) amplitude of all the harmonic components to the RMS amplitude of the fundamental frequency. The formula is often expressed as a percentage:

$$THD_{\%} = 100 \cdot \sqrt{\frac{H_2^2+H_3^2+\cdots H_n^2}{H_1^2}}, \qquad (5)$$

where H_1 represents the amplitude of the fundamental frequency, while H_2, H_3, and so on represent the amplitudes of the harmonic components. THD is often expressed in decibels (dB), which is a logarithmic unit used to describe the level of distortion. The formula is

$$THD_{dB} = 10 \cdot \log_{10}\left(\frac{THD_{\%}}{100}\right). \qquad (6)$$

This characteristic is a critical metric for assessing the linearity and fidelity of audio and video equipment. In audio applications, lower THD values indicate cleaner and more accurate sound reproduction. THD is also used in characterizing the performance of ADCs, amplifiers, and other electronic components. Lower THD values suggest better linearity and less distortion.

Lower THD values are generally desirable, indicating that the device introduces less harmonic distortion and produces a more faithful reproduction of the input signal. In audio equipment, THD values below 1% or even lower are often considered excellent.

THD analysis can be sensitive to measurement conditions and equipment calibration. Care must be taken to ensure that the test signal is accurately generated, and noise from external sources is minimized. While THD analysis is most commonly associated with audio equipment, it is also used in RF (radio frequency) and microwave systems to assess the linearity of amplifiers and signal processing components. In some cases, multiple sinusoidal tones are used as input signals to characterize THD across a range of frequencies.

In summary, THD analysis is a valuable technique for quantifying harmonic distortion in electronic devices. It plays a crucial role in assessing the linearity and fidelity of audio equipment and other systems where accurate signal reproduction is essential.

5. Linearity Testing

Linearity testing is a crucial evaluation process used to assess how well an electronic component or system, such as an analog-to-digital converter (ADC), adheres to a linear response. In linearity testing, the focus is on determining if the device produces an output that is directly proportional to the input, without introducing nonlinear distortion.

The primary purpose of linearity testing is to ensure that the device or system responds accurately and linearly to changes in input amplitude. It is particularly important in applications where precision and accuracy are critical, such as measurement and control systems.

In linearity testing, a test signal is typically generated. This signal can be a pure sinusoidal wave, a step function, or other controlled input signals. The signal generator produces a range of amplitudes that span the intended operating range of the device under test. The output of the device under test (DUT) is monitored and measured as it responds to the varying input amplitudes. The output can be captured using test equipment such as oscilloscopes, data acquisition systems, or specialized linearity measurement instruments [29]-[30].

Linearity error is a key parameter in linearity testing. It quantifies how far the actual output deviates from the ideal linear response [31]. Integral Nonlinearity (INL) is a metric used in linearity testing, particularly for ADCs. It measures the deviation of the actual transfer function from an ideal straight line. INL is often expressed in LSB or as a percentage of the LSB value. Differential Nonlinearity (DNL) is a closely related metric for ADCs. It quantifies the difference between the actual and expected step sizes between adjacent digital codes. DNL is typically expressed in LSB.

An ideal linear response implies that a change in the input signal by a certain amount should result in an exactly proportional change in the output signal. In the case of ADCs, a one-unit change in the input should result in a one-unit change in the output (1 LSB change).

The Histogram Test Method, also known as the Code Density Method [32]-[34], is a technique used to evaluate the linearity of analog-to-digital converters (ADCs). This method assesses the distribution of digital output codes relative to the input voltage levels to determine linearity errors. The primary goal of this method is to quantify linearity errors in an ADC by analyzing the distribution of digital output codes across its input voltage range. It provides insights into how accurately the ADC digitizes analog input voltages and identifies nonlinearities or code errors.

The test signal consists of a sinewave. The ADC under test is configured to convert the test signal into digital output codes. The digital output codes are collected and recorded as the input voltage varies. The collected digital output codes are grouped into bins or buckets based on their values. Each bin represents a specific range of digital codes. A histogram is created by counting the number of times each digital code falls into each bin. Nonlinearities in the ADC's response are detected by observing variations in the histogram. If the ADC exhibits nonlinear behavior, certain bins may contain more or fewer codes than expected. Linearity errors are calculated by comparing the actual histogram to the expected distribution. Linearity error is typically expressed as a percentage or in LSB (least significant bit). The

The Histogram Test Method is particularly useful for detecting subtle nonlinearities that may not be apparent in traditional linearity tests. It provides a comprehensive view of the ADC's behavior across its input range. Care should be taken when selecting the resolution of the test signal and the number of bins to ensure that linearity errors are accurately detected. Calibration and correction techniques may be applied based on the results of the Histogram Test to improve ADC performance.

In ADCs, linearity testing is critical to ensure that the device provides accurate digital representations of analog signals over a wide range of amplitudes. Some systems employ calibration techniques to correct for linearity errors and achieve improved performance. Linearity testing is a fundamental evaluation process used to determine how accurately an electronic device or system responds to changes in input amplitude. It is vital for ensuring precision and accuracy in various applications, from analog and digital signal processing to control and measurement systems.

6. Spurious-Free Dynamic Range

Spurious-Free Dynamic Range (SFDR) measurement is a crucial evaluation technique used to assess the performance of analog-to-digital converters and other electronic systems by quantifying the ability of the device to reject or minimize unwanted spurious signals in its output. SFDR is an essential parameter, particularly in applications where high-quality signal processing and noise rejection are required.

The primary purpose of SFDR measurement is to determine how well an ADC or electronic system can maintain the quality of its primary signal (fundamental) while minimizing the presence of spurious signals (distortions or harmonics) in the output. SFDR is crucial in applications like RF (radio frequency) communications, radar, and high-performance data acquisition systems.

In SFDR measurement, a pure sinusoidal signal, known as the fundamental signal, is typically generated. The frequency and amplitude of this fundamental signal are specified. The fundamental signal is usually chosen to be within the ADC's specified bandwidth. Spurious signals refer to any undesired signal components present in the ADC's output that are not part of the fundamental signal. These can include harmonics, intermodulation products, and other distortions. The ADC is configured to convert the fundamental signal and any associated spurious signals into digital output codes. The digital output codes are collected and recorded for analysis.

The collected digital output codes are analyzed in the frequency domain using a spectrum analyzer or similar equipment. The goal is to identify and measure the amplitudes of the spurious signals in the output.

SFDR is calculated as the ratio of the amplitude of the fundamental signal (desired signal) to the amplitude of the most significant spurious signal (largest undesired signal),

$$SFDR_{dB} = 20 \cdot \log_{10}\left(\frac{A}{A_{spurious}}\right). \quad (7)$$

SFDR is closely related to the concept of dynamic range. Dynamic range represents the range between the strongest and weakest signals that an ADC can accurately handle. The SFDR value represents the lowest level of an unwanted signal relative to the fundamental signal. A high SFDR value indicates that the ADC or electronic system effectively rejects or suppresses spurious signals, producing a clean output. SFDR is a critical parameter in applications where maintaining signal integrity is essential, such as in wireless communications and radar systems. Some systems employ calibration techniques to correct for spurious signals and improve SFDR performance. SFDR measurement can be challenging due to the need for precise signal generation and measurement equipment. Noise and interference can also affect the accuracy of SFDR measurements.

In summary, SFDR measurement is a vital technique for assessing the ability of ADCs and electronic systems to maintain signal integrity by minimizing unwanted spurious signals in the output. It is a key parameter in high-performance applications where high-quality signal processing and noise rejection are critical.

7. Intermodulation Distortion Testing

Intermodulation Distortion (IMD) testing is a technique used to assess the performance of analog-to-digital converters (ADCs) and other electronic devices by examining their response to the generation of unwanted signal products when two or more sinusoidal input signals are applied simultaneously. IMD testing aims to identify and quantify distortion products generated within the device under test (DUT) due to nonlinearity in its components or circuitry. It is particularly important in scenarios where multiple signals are present simultaneously, such as in wireless communication systems where multiple frequency components interact.

In IMD testing, typically two sinusoidal signals, referred to as "tones," are applied to the input of the ADC or DUT. These tones often have specific frequencies, amplitudes, and phase relationships. The frequencies of the tones are chosen to be within the operational bandwidth of the DUT. The goal is to evaluate the DUT's response when these tones interact nonlinearly. Nonlinearity within the DUT can cause the generation of new frequencies in the output signal, referred to as "intermodulation products" or "IM products." These IM products are generated by the nonlinear mixing of the input tones and can manifest as unwanted spectral components in the output signal. After applying the input tones and capturing the DUT's output, the spectral content of the output signal is analyzed. The presence and magnitude of IM products are measured and compared to the desired response (i.e., a linear response without distortion). Common parameters used for IM product characterization include third-order intercept point (IP3) and the 1st, 2nd, and 3rd order intermodulation distortion products (IMD1, IMD2, IMD3).

Another important parameter is the third-order intercept point (IP3). It represents the point at which the third-order intermodulation products intersect the input signal's power level. A higher IP3 value indicates that the DUT can handle higher input power levels before significant distortion occurs. IP3 is often used to quantify the linearity of amplifiers and other RF components.

IMD testing is widely used in the design and evaluation of RF (radio frequency) and microwave systems, such as in wireless communication infrastructure and RF transceivers. It helps engineers ensure that RF components, including ADCs, do not introduce unacceptable levels of distortion in real-world conditions with multiple signals. IMD testing can be more complex than single-tone testing, as it involves the simultaneous application of multiple signals with specific relationships. Careful calibration and signal generation are required to achieve accurate and repeatable results.

In summary, IMD testing is a valuable technique for evaluating the linearity and distortion characteristics of ADCs and other electronic devices in scenarios where multiple input signals interact. It helps ensure that these devices perform accurately and without introducing unacceptable distortion when faced with real-world signal conditions.

8. Conclusions

There are numerous applications that use sinusoidal signals as stimulus and that measure the response of those systems and expect to observe sinusoidal signals. Deviation for the expected are used to quantify the behavior of the system under test. In the case of ADCs there are particular tests that can be carried out to access their metrological characteristics and which are regularly used by engineers.

Compliance with ethical standards

Acknowledgments

This work was supported in by Fundação para Ciência e a Tecnologia under the research projects UIDB/50008/2020 and FCT.CPCA.2022.01 whose support the author gratefully acknowledges.

F. A. C. A. is with Instituto de Telecomunicações and Instituto Superior Técnico, Technical University of Lisbon, Portugal,

Disclosure of conflict of interest

No conflict of interest to be disclosed.

References

[1] IEEE, "Standard 1057-1994 - IEEE Standard for Digitizing Waveform Recorders", December 1994.

[2] IEEE, "Approved Draft Standard for Terminology and Test Methods for Analog-to-Digital Converters", June 2023.

[3] Brian D'Andrade, "The Power Grid", Academic Press, March 2017, ISBN: 9780081009529.

[4] D. Sundararajan, "Fourier Analysis - A Signal Processing Approach", Springer Singapore, https://doi.org/10.1007/978-981-13-1693-7.

[5] C. Nataraj, "Vibration of Mechanical Systems", Cengage Learning, March 2012, ISBN: 978-1408072653.

[6] F. Gueuning, M. Varlan, C. Eugene and P. Dupuis, "Accurate distance measurement by an autonomous ultrasonic system combining time-of-flight and phase-shift methods," Quality Measurement: The Indispensable Bridge between Theory and Reality (No Measurements? No Science! Joint Conference - 1996: IEEE Instrumentation and Measurement Technology Conference and IMEKO Tec, Brussels, Belgium, 1996, pp. 399-404 vol.1, https://doi.org/10.1109/IMTC.1996.507414.

[7] R. Queirós, F. C. Alegria, P. S. Girão, A. C. Serra, "A multi-frequency method for ultrasonic ranging" Ultrasonics vol. 63, pp. 86-93, December 2015, https://doi.org/10.1016/j.ultras.2015.06.018.

[8] O. Birjukova, S Guillén Ludeña, F Alegria, AH Cardoso, "Three dimensional flow field at confluent fixed-bed open channels", Proceedings of River Flow 2014, pp. 1007-1014, 2014, ISBN: 978-1-138-02674-2.

[9] O. Birjukova Canelas, RML Ferreira, S Guillén-Ludeña, FC Alegria, AH Cardoso, "Three-dimensional flow structure at fixed 70º open-channel confluence with bed discordance", Journal of Hydraulic Research 58 (3), 434-446, 2020, https://doi.org/10.1080/00221686.2019.1596988.

[10] S. Guillén-Ludeña, M. J Franca, F. Alegria, A.J. Schleiss, A.H. Cardoso, "Hydromorphodynamic effects of the width ratio and local tributary widening on discordant confluences", Geomorphology, vol. 293, pp. 289-304, September 2017, https://doi.org/10.1016/j.geomorph.2017.06.006.

[11] O. Postolache, H. G. Ramos, A. Lopes Ribeiro, F. Corrêa Alegria, "GMR Based Eddy Current Sensing Probe for Weld Zone Testing", Proceedings of the IEEE 2009 Sensors Conference in Christchurch, New Zealand, 26-28 October 2009, pp. 73-78, https://doi.org/10.1109/ICSENS.2009.5398524.

[12] Michael R. Matthews, Colin F. Gauld, Arthur Stinner editors, "The Pendulum - Scientific, Historical, Philosophical and Educational Perspectives", Springer Dordrecht, January 2016, https://doi.org/10.1007/1-4020-3526-8.

[13] James T. Cushing, "The spring-mass system revisited", American Journal of Physics vol. 52, pp. 925–933, October 1984, https://doi.org/10.1119/1.13796.

[14] David Tse, Pramod Viswanath, "Fundamentals of Wireless Communication", Cambridge University Press, 2005, ISBN: 978-0521845274.

[15] Tore Hagglund, "PID Controllers: Theory, Design, and Tuning", 2nd edition, ISA: The Instrumentation, Systems, and Automation Society, January 1995, ISBN: 978-1556175169.

[16] Andrea Pejrolo, Scott B. Metcalfe, "Creating Sounds from Scratch: A Practical Guide to Music Synthesis for Producers and Composers", Oxford University Press, February 2017, ISBN: 978-0199921898.

[17] F. Corrêa Alegria, "Sensors and Actuators", World Scientific, July 2021, ISBN: 978-9811242496.

[18] Tanjina Nur, editor, "Seismology, Earthquake Engineering and Structural Engineering", Arcler Education Inc., December 2018, ISBN: 978-1773613772.

[19] Ahmed El-Rabbany, "Introduction to GPS: The Global Positioning System", Artech House, 2002, ISBN: 978-1580531832.

[20] M. Born, E. Wolf, A. B. Bhatia, P. C. Clemmow, D. Gabor, A. R. Stokes, A. M. Taylor, P. A. Wayman, W. L. Wilcock, "Principles of Optics: Electromagnetic Theory of Propagation, Interference and Diffraction of Light", 7th edition, Cambridge University Press, October 1999, ISBN: 978-0521642224.

[21] E. Martinho, F. Corrêa Alegria, A. Dionisio, C. Grangeia, F. Almeida, "3D resistivity imaging and distribution of water soluble salts in Portuguese Renaissance stone bas-reliefs", Engineering Geology, vol. 141, pp. 33 44, April 2012, https://doi.org/10.1016/j.enggeo.2012.04.010.

[22] F. Corrêa Alegria, A Cruz Serra, "Error in the estimation of transition voltages with the standard histogram test of ADCs", Measurement, vol. 35, no. 4, pp. 389-397, 2004, https://doi.org/10.1016/j.measurement.2004.03.003.

[23] F. Corrêa Alegria, A Cruz Serra, "Influence of frequency errors in the variance of the cumulative histogram [in ADC testing]", Transactions on Instrumentation and Measurement, vol. 50, no. 2, pp. 461-464, April 2001, https://doi.org/10.1109/19.918166.

[24] F. Corrêa Alegria, A. Cruz Serra, "Uncertainty of the estimates of sine wave fitting of digital data in the presence of additive noise", 2006 IEEE Instrumentation and Measurement Technology Conference Proceedings, 2006, https://doi.org/10.1109/IMTC.2006.328187.

[25] I. Kollar and J. J. Blair, "Improved determination of the best fitting sine wave in ADC testing," in IEEE Transactions on Instrumentation and Measurement, vol. 54, no. 5, pp. 1978-1983, Oct. 2005, DOI: https://doi.org/10.1109/TIM.2005.855082.

[26] F. Corrêa Alegria and A. Cruz Serra, "Uncertainty of ADC Random Noise Estimates Obtained with the IEEE 1057 Standard Test", IEEE Transactions on Instrumentation and Measurement, vol. 54, No. 1, February 2005, DOI: https://doi.org/10.1109/TIM.2004.840226.

[27] D. B. Leeson, "Oscillator Phase Noise: A 50-Year Review," in IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control, vol. 63, no. 8, pp. 1208-1225, Aug. 2016, https://doi.org/10.1109/TUFFC.2016.2562663.

[28] S. Shariat-Panahi, F. Corrêa Alegria, A. Mànuel, A. Cruz Serra, "IEEE 1057 jitter test of waveform recorders", IEEE Transactions on Instrumentation and Measurement 58 (7), 2234-2244, 2009, https://doi.org/10.1109/TIM.2009.2013674.

[29] F. Corrêa Alegria, Pedro Girão, Vladimir Haasz and António Serra, "Performance of Data Acquisition Systems from User's Point of View", IEEE Instrumentation and Measurement Technology Conference, Vail, Colorado, USA, pp. 940-945, 20-22 May 2003, https://doi.org/10.1109/IMTC.2003.1207891.

[30] F. Corrêa Alegria, P. Girão, V. Haasz, A. Cruz Serra, "Performance of Data Acquisition Systems from the User's Point of View", IEEE Transactions on Instrumentation and Measurement, vol. 53, nº 4, pp. 907 914, August 2004, https://doi.org/10.1109/TIM.2004.830757.

[31] F. Corrêa Alegria, A. Moschitta, P. Carbone, A. Cruz Serra, D. Petri, "Effective ADC linearity testing using sinewaves", IEEE Transactions on Circuits and Systems I: Regular Papers 52 (7), 1267-1275, 2005, https://doi.org/10.1109/TCSI.2005.851393.

[32] Björsell, Niclas & Händel, Peter. (2005). A statistical evaluation of ADC histogram tests with arbitrary stimuli signal. https://doi.org/10.1049/cp:20050168.

[33] A. Cruz Serra, F. Corrêa Alegria, L. Michaeli, P. Michalko, J. Saliga, "Fast ADC testing by repetitive histogram analysis", 2006 IEEE Instrumentation and Measurement Technology Conference Proceedings, 2006, https://doi.org/10.1109/IMTC.2006.328161.

[34] F. Corrêa Alegria, A. Cruz Serra, "Uncertainty in the ADC transition voltages determined with the histogram method" Proceedings of the 6th Workshop on ADC Modeling and Testing, Lisbon, 2001, ISBN 972-98115-5-5.

[35] F. Corrêa Alegria and A. Cruz Serra, "Influence of Frequency Errors in the Variance of the Cumulative Histogram", IEEE Transactions on Instrumentation and Measurements, vol. 50, n. 2, pp. 461-464, April 2001, https://doi.org/10.1109/CPEM.2000.851145.