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(REVIEW ARTICLE)

Better approximation for the precision of the number of counts in the histogram test of ADCs

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Abstract

Here one proposes a new analytical expression that can be used to estimate the precision of the estimates made with the histogram test of analog-to-digital converters as a function of the additive noise standard deviation present in the test setup. This can be advantageously used to determine the minimum samples that should be acquired in order to achieve a certain level of precision on the estimates made. A more rigorous choice of the number of samples makes the characterization more efficient and less time consuming.

Keywords: Analog-to-digital converter; Characterization; Histogram Test Method; Precision; Approximate Expression

1. Introduction

Analog-to-digital converters (ADCs) are critical components in modern electronic systems due to their versatile role in various applications [1]. ADCs facilitate the conversion of continuous analog signals, such as sound, temperature, and light, into discrete digital values [2]. These digital values can be processed, analyzed, and stored by digital devices like microcontrollers, FPGAs, and computers. They are essential for maintaining precision and accuracy in measurements and control systems, ensuring that even minute variations in input signals are accurately captured and preserved [3]. They play a vital role in digital signal processing (DSP), enabling operations such as filtering, modulation, demodulation, and Fourier analysis. DSP techniques, in turn, support advanced functions like noise reduction, image processing, and communication systems [4].

There are numerous applications where ADCs play a fundamental role. In communication systems, ADCs encode analog signals (e.g., audio, video, RF) into digital formats, allowing for efficient transmission, storage, and processing of information. This underpins technologies like digital television, wireless communication, and the internet [5]. ADCs are fundamental for the Internet of Things (IoT), as they convert sensor data, often in analog form, into digital data for analysis and transmission. This is crucial for applications in smart devices, environmental monitoring, and wearable technology. Consumer electronics, such as audio recording and playback systems and digital cameras, rely on ADCs for high-quality sound capture, video recording, and image processing. Industrial automation and control systems benefit from ADCs, which interface with sensors and actuators to convert sensor readings into digital values for processing by control algorithms [6]. In healthcare, ADCs are integral to medical imaging devices, patient monitors, and diagnostic equipment, converting biological signals (e.g., ECG, EEG) into digital data for analysis and diagnosis [7]. By digitizing analog signals, ADCs enable efficient digital processing, which reduces power consumption and is particularly important in battery-powered devices and green energy applications [8].

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In summary, ADCs serve as crucial bridges between the analog and digital domains, facilitating the integration of various technologies that impact our daily lives, from smartphones and smart homes to healthcare, communications, and industrial automation.

2. Histogram Test Method

The Histogram Test Method, also known as the Code Transition Test Method, is a crucial tool for analog-to-digital converter (ADC) characterization and performance evaluation [9]-[11]. It involves analyzing how the ADC transitions between digital output codes in response to changes in its analog input. This testing provides valuable insights into the ADC's linearity, quantization error, and ability to accurately represent analog signals with discrete digital codes [12].

The Histogram Test helps assess the linearity of an ADC [13]-[15]. Linearity refers to how closely the ADC's output follows a straight-line transfer function, ideally mapping analog input values to digital output codes with uniform spacing. A known and controlled analog input signal is applied to the ADC. This signal can be a continuous waveform or a set of discrete voltage levels. The ADC samples the continuous analog signal at a specified rate, generating a sequence of digital output codes. The digital output codes are collected and analyzed. One common way to perform Code Transition Testing is by creating a histogram of the collected digital codes. In this histogram, the x-axis represents the digital code values, and the y-axis represents the frequency of occurrence of each code value [3].

There are two ways to specify the non-linearity of an ADC: 1) differential Non-Linearity (DNL) measures the deviation between the actual step size of the ADC and the ideal step size. DNL can be determined by examining the spacing between adjacent histogram bins. Ideally, DNL should be very close to zero, indicating a linear mapping of input to output codes; 2) Integral Non-Linearity (INL) assesses the cumulative deviation of the ADC's output from the ideal straight-line characteristic. It is determined by summing the DNL values across all code transitions. A smaller INL value indicates better linearity [16]-[17].

A well-behaved ADC will exhibit a histogram with nearly uniform distribution of codes, meaning that each digital code appears with roughly equal frequency. Ideally, the digital codes should be evenly spaced, reflecting a linear relationship between analog input and digital output. Any deviations from this ideal behavior, such as code clustering, missing codes, or uneven spacing, can indicate non-linearity issues in the ADC.

Code Transition Testing is critical for applications where precise analog-to-digital conversion is required, such as in measurement instruments, audio processing, and communication systems. It helps identify and quantify non-linearities and distortion in the ADC, enabling manufacturers and engineers to calibrate or compensate for these errors when necessary.

In summary, Code Transition Testing is a valuable technique for evaluating the linearity and accuracy of an ADC. It provides a quantitative assessment of how well an ADC translates analog input signals into digital codes and is an essential step in ensuring the overall performance of the ADC in various applications.

These parameters are derived from the number of counts of the histogram. The number of counts becomes a random variable when non-deterministic phenomena are present like additive voltage noise, phase noise or jitter and can become biased when other non-ideal phenomena are present like frequency error on the clock of the stimulus signal [18]. This paper deals with the precision of the number of counts of the cumulative histogram in the presence of additive noise only.

The sinusoidal signals used to characterize ADCs are very common and are used in numerous applications like distance [19] and velocity [20]-[22] measurement using ultrasounds, for example.

Naturally when using sinusoidal models to fit data points [23], the presence of noise will also have an effect on the uncertainty of the estimates made [24]-[26]. Even the estimation of the amount of noise itself is subject to estimation uncertainty [27].

3. Number of Counts in the Cumulative Histogram

The number of counts of the cumulative histogram is the first random variable to be built in the path to the determination of other ADC characteristics like transition voltages [28], using

$$\hat{T}_k = C - A \cdot \cos\left(\frac{c_{k-1}}{M}\right) \ , \ k = 1, 2, \dots, 2^{n_b} - 1, \dots\dots\dots(1)$$

where M is the number of samples acquired, the code bin withs, INL, DNL, gain and offset error.

A Monte Carlo procedure was used to obtain the variance of the number of counts of the cumulative histogram, $\sigma_{c_k}^2$, for the different transition voltages, U_{k+1}, and different amount of additive noise standard deviation (normalized by the stimulus signal amplitude), σ_n. An example of that for the case of 5 samples can be observed in Figure 1.

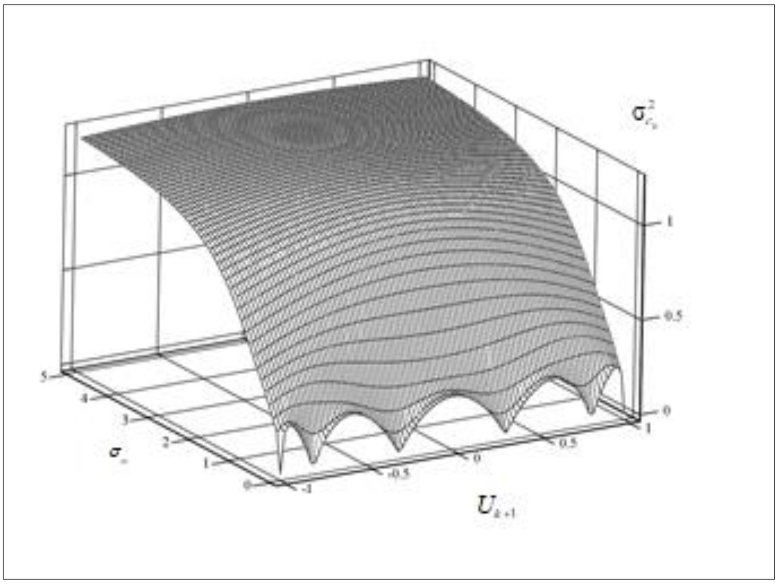

Figure 1 Variance of the number of counts of the cumulative histogram as a function of the normalized additive noise standard deviations and the transition voltage in the case of 5 acquired samples

In the limit case of no noise preset, $\sigma_n = 0$, one can see a number of arcs equal to the number of samples, M. In this case there were 5 samples acquired (for illustrative purposes). A more realistic case with 100 samples can be observed in Figure 2.

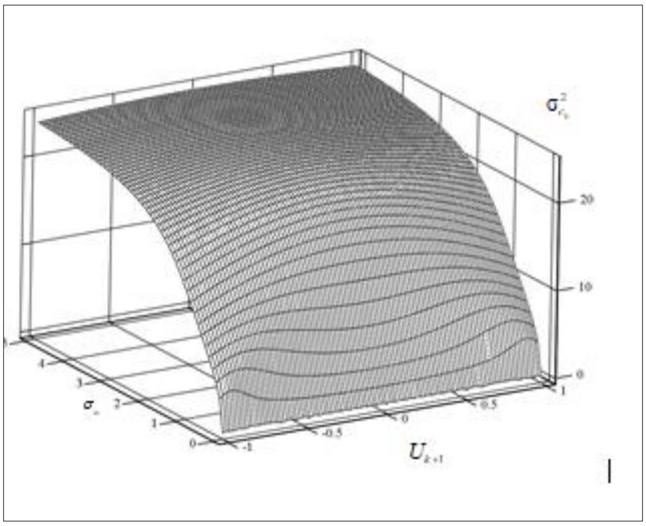

Figure 2 Variance of the number of counts of the cumulative histogram as a function of the normalized additive noise standard deviations and the transition voltage in the case of 100 acquired samples

The higher is the amount of additive noise present, the higher is the variance of the number of counts of the cumulative histogram, $\sigma_{c_k}^2$. Representing the highest value of that variance among all transition voltages one gets the chart in Figure 3 (thick solid line).

In previous works related to the uncertainty of the estimates made with the histogram test method [28]-[29] one has approximated that uncertainty by the thin solid line in Figure 3 given by

$$\sigma_{c_k}^2 \approx \max\left(\frac{1}{4}, M \cdot \min\left(\frac{1}{4}, \frac{\sigma_n}{\pi\sqrt{\pi}}\right)\right), \ldots\ldots\ldots\ldots (2)$$

which, for a reasonable number of samples is approximately equal to

$$\sigma_{c_k}^2 \approx \min\left(\frac{M}{4}, \frac{\sigma_n}{\pi\sqrt{\pi}}\right) \ldots\ldots\ldots\ldots (3)$$

The main goal of this work is to propose a better analytical approximation (dashed line).

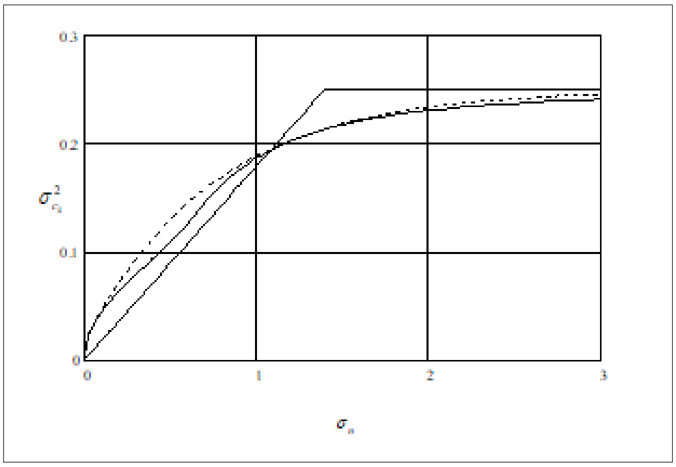

Figure 3 Variance of the number of counts of the cumulative histogram as a function of the normalized additive noise standard deviations in the case of 100 acquired samples (solid line). The dotted line is the old approximation, and the dashed line is the approximation proposed here

That was achieved using an exponential model given by

$$\sigma_{c_k}^2 \approx M \cdot \left[0.0155 + \left(\frac{1}{4} - 0.0155\right) \cdot \left(1 - e^{-1.35 \cdot \sigma_n}\right)\right] \ldots\ldots\ldots\ldots (4)$$

The two free parameters, 0.0155 and 1.35 were obtained by trial and error to lead to the smallest error possible that was still positive. That error can be seen in

Figure 4.

One can see how closely the dashed curve follows the thick solid curve in Figure 3. A better approximation could be obtained at the expense of a more convoluted mathematical expression. One feels that this is not justified since the amount of additive noise present, σ_n, is often also an estimative which is usually higher than the actual value but, in any case, not known with great accuracy. Obtaining a more fitting analytical expression would thus be an “overkill”.

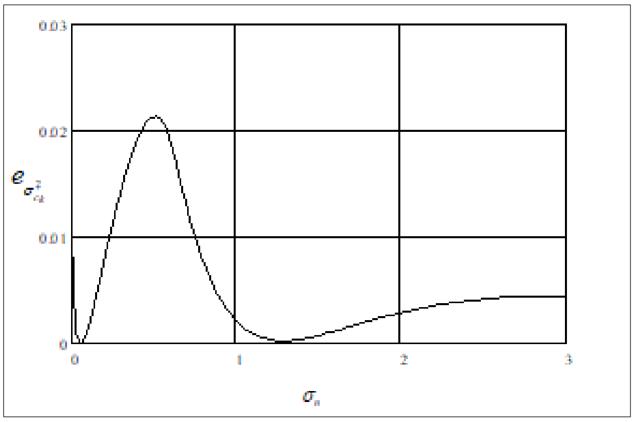

Figure 4 Variance of the number of counts of the cumulative histogram as a function of the normalized additive noise standard deviations in the case of 100 acquired samples (solid line). The dotted line is the old approximation, and the dashed line is the approximation proposed here

Note that one wanted the error to be always positive so that the variance given by the analytical model proposed is always higher that the real variance and thus lead to larger confidence levels for the ADC parameters estimated from the number of counts of the cumulative histogram like the transition voltages given by

$$\sigma_{\hat{T}}^2 \approx \left(\frac{A\pi}{M}\right)^2 \cdot \sigma_{c_k}^2 \ldots\ldots\ldots\ldots(5)$$

The values of normalized additive noise standard deviation used in the simulation of

Figure 4 are rather large, A similar chart is shown here in Figure 5 that covers a more realistic range where the additive noise standard deviation goes up to 20% of the stimulus signal amplitude.

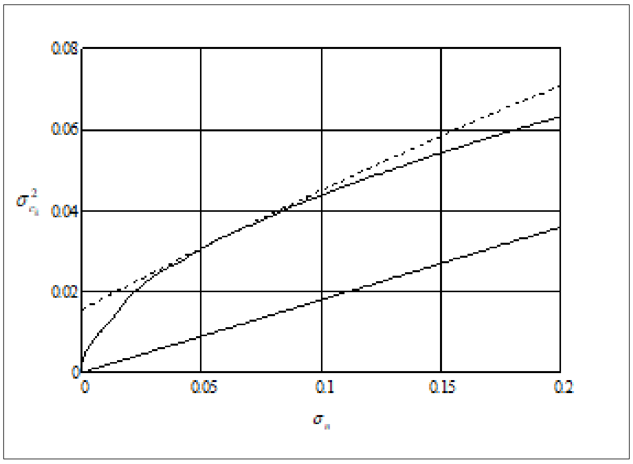

Figure 5 Variance of the number of counts of the cumulative histogram as a function of the normalized additive noise standard deviations in the case of 100 acquired samples (solid line). The dotted line is the old approximation, and the dashed line is the approximation proposed here

It may be seen how much better the currently proposed expression, eq. (4), is relative to the previous one, eq. (2).

One can go to the variance of the transition voltages by inserting (4) into (5) leading to

$$\sigma_{\hat{T}}^2 \approx \frac{A^2\pi^2}{M} \cdot \left[0.0155 + \left(\frac{1}{4} - 0.0155\right) \cdot \left(1 - e^{-1.35\cdot\sigma_n}\right)\right] \ldots\ldots\ldots(6)$$

Using the now proposed expression leads to a more accurate estimation of the variance of the number of counts and consequently the variance of the estimated transition voltages. Note that knowing this variance is fundamental for the determination of confidence intervals for the estimated ADC parameters derived from this number of counts of the cumulative histogram. It is also important in order to choose the number of samples to use given a desired upper bound for the variance, $B_{\sigma_{\hat{T}}^2}$:

$$M > \frac{A^2\pi^2}{B_{\sigma_{\hat{T}}^2}} \cdot \left[0.0155 + \left(\frac{1}{4} - 0.0155\right) \cdot \left(1 - e^{-1.35\cdot\sigma_n}\right)\right] \ldots\ldots\ldots(7)$$

This allows the engineer to choose the correct number of samples to use and thus limit the test duration.

4. Conclusion

This paper proposed a new and more accurate analytical expression to be used for the variance of the number of counts of the cumulative histogram in the code density test method of ADCs, namely eq. (4). For the case of estimating the transition voltages one proposes eq. (6).

This is fundamental in order to choose the number of samples that need to be acquired in order to achieve a certain desired level of precision on the estimates made. Using the proposed expression allows for a more efficient ADC test carried out in a shorter time frame.

Future work may be carried out on the case of other non-ideal phenomena present like jitter or phase noise.

Compliance with ethical standards

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