World Journal of Advanced Engineering Technology and Sciences
eISSN: 2582-8266
Cross Ref DOI: 10.30574/wjaets
Journal homepage: https://wjaets.com/

(Research Article)

USING SINUSOIDAL INSTEAD OF TRIANGULAR STIMULUS SIGNALS ON THE IEEE 1057 STANDARD RANDOM NOISE TEST OF ADCS

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World Journal of Advanced Engineering Technology and Sciences, 2026, 20(02), 169–174

Publication history: Received on 01 July 2026; revised on 17 August 2026; accepted on 19 August 2026

Article DOI: https://doi.org/10.30574/wjaets.2026.20.2.0405

ABSTRACT

The random-noise test for analog-to-digital converters (ADCs) prescribed by the IEEE Standard 1057 for Digitizing Waveform Recorders relies on a triangular signal to stimulate the converter under test. This paper shows that a sinusoidal stimulus may be used in its place without changing the estimator. Doing so makes the test more flexible and, more importantly, opens the way to sine-fitting algorithms for recovering the initial phase of the two data records that the test requires. Once known, this initial phase allows the two records to be aligned, reducing the error that additive noise introduces through the acquisition trigger. It is proved that the estimator obtained for the sinusoidal case coincides with the one recommended by the standard for the triangular case, and the two are compared, together with the direct-current case, both analytically and through their expected values and errors.

Keywords: Analog-to-digital converter; ADC testing; Random noise test; IEEE 1057; Sine wave; Sine fitting; Measurement uncertainty.

1 INTRODUCTION

The standard deviation of the random noise present in an analog-to-digital converter (ADC) is a key figure of merit, both for describing converter performance and for choosing a device suited to a given application. Its value in a particular test setup is also needed in other ADC tests — such as the standard static test [1] and the standard histogram test [1]–[7] — where it enters the evaluation of the error and precision of the estimated parameters.

The precision of the estimates delivered by this test was analyzed in [8], where an expression was also derived for the minimum number of samples needed to keep the uncertainty of the result within a prescribed bound. Knowing this number matters in practice, since it allows the test to be made no longer than necessary.

Naturally, other quantities that are estimated using data acquired with ADCs will also have an associated uncertainty that is important to quantify. This can be, for example, the estimation of defects on conductive materials using eddy currents [9] or the estimation of flow velocity in some hydraulic applications [10].

As described in [1], section 8.6.2, the test consists of acquiring synchronously two records of M samples each. The noise standard deviation (σ_r) is then estimated from the root-mean-square difference (msd) between the output codes of the two records. When the noise is large enough, a null input suffices; otherwise the standard prescribes a triangular stimulus signal.

This paper argues that a sinusoidal stimulus can serve equally well. Beyond the added flexibility this brings to the measurement, its chief advantage is that it makes the usual sine-fitting algorithms applicable for recovering the initial phase of the two records. Two records are needed so that, on subtracting one from the other, the systematic contributions — ADC non-linearity, gain and offset error, stimulus distortion — cancel, leaving only random effects such as additive noise. Because other random contributions (amplitude or phase noise of the stimulus, ADC jitter) also survive the subtraction, the quantity the test returns is in fact an upper bound on the additive random noise of the converter. For the systematic errors to cancel, the two records must be perfectly aligned, that is, acquisition must begin at the same phase of the stimulus in both. The IEEE 1057 standard secures this by triggering the acquisition on the stimulus voltage; that trigger, however, is itself perturbed by amplitude noise, since the instant of the first sample then depends not only on the ideal stimulus value but also on the random noise voltage present at that moment.

Curve fitting could in principle be carried out on a triangular signal as well, but triangular-fitting procedures are considerably less straightforward than sine-fitting ones.

What follows shows that a sinusoidal stimulus can indeed be used and that it leads to exactly the same estimator as the triangular one. That is the goal of the paper; the precise way in which the sine-fitting information is used to align the records, and a quantitative assessment of how much this improves on the conventional procedure, are left to a future publication.

Section 2 derives the variance of the ADC output codes for three kinds of stimulus — constant (DC), triangular and sinusoidal. Section 3 obtains the estimator for the sinusoidal case and compares it with the DC and triangular ones. Section 4 draws the conclusions.

2 VARIANCE OF THE ADC OUTPUT CODES

2.1 DC stimulus signal

Random additive noise in an ADC, as characterized in [1], is a non-deterministic fluctuation of the output described by its frequency spectrum and its statistical properties. It is customarily assumed to be white (flat spectrum), stationary in its probability density, additive and independent of the stimulus.

Because of this noise at the input, the output code (k) is a discrete random variable that may take any value between 0 and $2^{n_b}-1$ for an n_b-bit converter.

When the noise standard deviation exceeds the ideal code bin width (Q), the method of [1] is to short-circuit the input, acquire two records (ka_j and kb_j) and subtract their codes. The subtraction removes the fixed errors of the converter while preserving the random character of the codes.

Throughout, voltages are normalized to the ideal code bin width Q and expressed in LSB (least-significant-bit) units. Writing y for the normalized stimulus voltage and r for the normalized noise voltage, the normalized sampled voltage at instant t_j is

$$u(t_j) = y(t_j) + r(t_j) \qquad (1)$$

With the normalized noise taken to have zero mean and standard deviation σ_r (=σ/Q), the sampled voltage — itself a random variable — has

$$\mu_u = y \quad and \quad \sigma_u = \sigma_r \qquad (2)$$

Since the additive noise is normal, the sampled-voltage probability density function is [11]

$$f_u(u|y) = \frac{1}{\sqrt{2\pi}\sigma_r} \cdot e^{\frac{-(u-y)^2}{2\sigma_r^2}} \quad (3)$$

and the corresponding distribution function is [11]

$$F_u(U|y) = \int_{-\infty}^{U} f_u(u)du = \frac{1}{2} + \frac{1}{2} \cdot erf\left(\frac{U-y}{\sqrt{2}\cdot\sigma_r}\right) \qquad (4)$$

Owing to the subtraction of the two records, the ADC may be treated as ideal — the fixed errors having been removed and the random ones referred to the stimulus input. The probability p_k that a sample yields code k equals the probability that the sampled voltage lies between the transition voltages $U[k]$ and U[k+1] (for the interior codes):

$$p_k = P(U[k] \leq u \leq U[k+1]) \ , \ k = 1, \dots, 2^{n_b} - 2 \ (5)$$

where the normalized transition voltage $U[k]$=T[k]/Q has been used. With the distribution function, p_k can be written as

$$p_k(y) = F_u(U[1]|y) \ , \ k = 0$$

$$p_k(y) = F_u(U[k+1]|y) - F_u(U[k]|y) \ , \ k = 1, \dots, 2^{n_b} - 2$$

$$p_k(y) = 1 - F_u(U[2^{n_b} - 1]|y) \ , \ k = 2^{n_b} - 1 \qquad (6)$$

By definition, the mean, second moment and variance of the output codes are [11]

$$\mu_{k|y} = \sum_{k=0}^{2^{n_b}-1} k \cdot p_k(y)$$

$$m_{2k|y} = \sum_{k=0}^{2^{n_b}-1} k^2 \cdot p_k(y)$$

$$\sigma_{k|y}^2 = m_{2k|y} - \mu_{k|y}^2 \qquad (7)$$

2.2 Triangular stimulus signal

When the noise is small compared with the ideal code bin width, the IEEE 1057 standard [1] recommends a triangular stimulus spanning several codes (about ten). The output-code variance follows from the amplitude distribution f_y of that stimulus [11]:

$$\sigma_k^2 = \int_{-\infty}^{\infty} \sigma_{k|y}^2(y) \cdot f_y(y)dy \qquad (8)$$

For a triangular signal of amplitude A and offset C, normalized to the code bin width (A_Q=A/Q and C_Q=C/Q), the amplitude distribution is

$$f_y(y) = \left\{\frac{1}{2A_Q} \ , \ |y - C_Q| < A_Q \ ; \quad 0 \ , \ otherwise\right\} \quad (9)$$

so that the output-code variance becomes

$$\sigma_k^2 = \frac{1}{2A_Q} \int_{C_Q-A_Q}^{C_Q+A_Q} \sigma_{k|y}^2(y)dy \qquad (10)$$

2.3. Sinusoidal stimulus signal

For a sinusoidal stimulus the variance is obtained in the same way, now using [11]

$$f_y(y) = \left\{\frac{1}{\pi\sqrt{A_Q^2 - (y - C_Q)^2}} \ , \ |y - C_Q| < A_Q \ ; \quad 0 \ , \ otherwise\right\} (11)$$

which, inserted into (8), gives

$$\sigma_k^2 = \int_{C_Q-A_Q}^{C_Q+A_Q} \sigma_{k|y}^2(y) \cdot \frac{1}{\pi\sqrt{A_Q^2 - (y - C_Q)^2}} dy \qquad (12)$$

3 RANDOM NOISE ESTIMATORS

The noise estimator is built from the mean-square difference

$$msd = \frac{1}{M}\sum_{j=0}^{M-1}\left(ka_j - kb_j\right)^2 \qquad (13)$$

Because the two records are independent, the mean-square difference has twice the variance of a single record; its expected value is therefore twice the output-code variance [11]:

$$E\{msd\} = \sigma_{ka}^2 + \sigma_{kb}^2 = 2\sigma_k^2 \qquad (14)$$

Since the output-code variance equals that of the additive noise, the estimated noise standard deviation is simply

$$\hat{\sigma}_r = \sqrt{\frac{msd}{2}} \qquad (15)$$

Its expected value can be approximated, using (14), by

$$E\{\hat{\sigma}_r\} \approx \sqrt{\frac{E\{msd\}}{2}} \quad (16)$$

which, on inserting (14), reduces to

$$E\{\hat{\sigma}_r\} \approx \sigma_k \qquad (17)$$

where σ_k is given by (8). As Fig. 1 shows, for small noise standard deviations this expected value departs markedly from the true noise standard deviation (dashed and dotted curves).

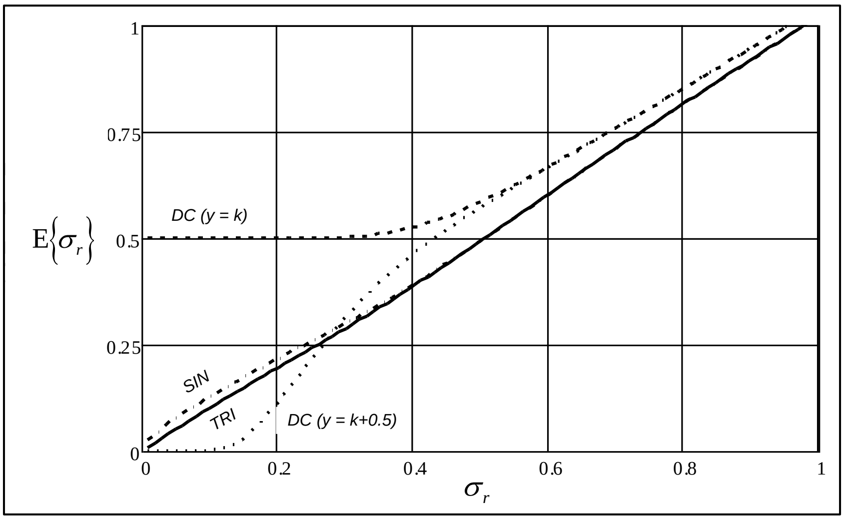

Figure 1: Expected value of the estimated random noise against the actual noise standard deviation, for a DC stimulus (dashed and dotted), a triangular stimulus (solid) and a sinusoidal stimulus (dash-dotted). The two DC curves correspond to a stimulus equal to an ADC transition voltage (dashed) and exactly midway between two consecutive transition voltages (dotted). The triangular and sinusoidal amplitudes are 5 LSB.

For a triangular stimulus the estimator recommended by IEEE 1057 is

$$\hat{\sigma}_r = \left[\left(\sqrt{\frac{msd}{2}}\right)^{-4} + \left(\frac{\sqrt{\pi}}{2}\cdot msd\right)^{-4}\right]^{\frac{-1}{4}} \qquad (18)$$

This form was obtained heuristically by joining the two limiting regimes: a large amount of random noise, eq. (15), and a small amount. The small-noise limit follows from (10) and (7), but with the stimulus spanning only two ADC codes, which gives

$$\sigma_k^2 = \frac{1}{2A_Q}\int_{C_Q-A_Q}^{C_Q+A_Q}\left[\frac{1}{4}-\frac{1}{4}\cdot erf^2\left(\frac{U[k]-y}{\sqrt{2}\cdot\sigma_r}\right)\right]dy \ \ , \ \sigma_r \ll 1 \qquad (19)$$

In the limit of a large amplitude and vanishing noise this reduces to

$$lim_{\sigma_r\to 0, A_Q\to\infty}\ \sigma_k^2 = \frac{1}{\sqrt{\pi}}\sigma_r \quad (20)$$

Combining (20) with (14), a candidate estimator for the small-noise regime is

$$\hat{\sigma}_r = \frac{\sqrt{\pi}}{2}\cdot msd \ \ , \ \sigma_r \ll 1 \quad (21)$$

It is (15) and (21) that combine to give (18). The expected value of (18) can be approximated by

$$E\{\hat{\sigma}_r\} \approx \left[\left(\sqrt{\frac{E\{msd\}}{2}}\right)^{-4} + \left(\frac{\sqrt{\pi}}{2}\cdot E\{msd\}\right)^{-4}\right]^{\frac{-1}{4}} \qquad (22)$$

and, on inserting (14), by

$$E\{\hat{\sigma}_r\} \approx \left[(\sigma_k)^{-4} + \left(\sqrt{\pi}\sigma_k^2\right)^{-4}\right]^{\frac{-1}{4}} \quad (23)$$

where σ_k is given by (10). This expected value is the solid curve in Fig. 1, which confirms that it estimates σ_r well.

A sinusoidal stimulus is handled by the same reasoning, replacing (9) and (10) with (11) and (12). For the extreme case of small noise and large amplitude the result is again (20), so the heuristic estimator for the sinusoidal case is identical to the triangular one, namely (18). Its expected value is shown as the dash-dotted curve in Fig. 1 and is seen to be very close to the triangular one (solid curve).

Fig. 2 shows the error of the estimators, defined as

$$e_{\hat{\sigma}_r} \triangleq E\{\hat{\sigma}_r\} - \sigma_r \qquad (24)$$

For small noise the triangular and sinusoidal estimators are far more accurate than the DC one; for large noise all three perform equally well.

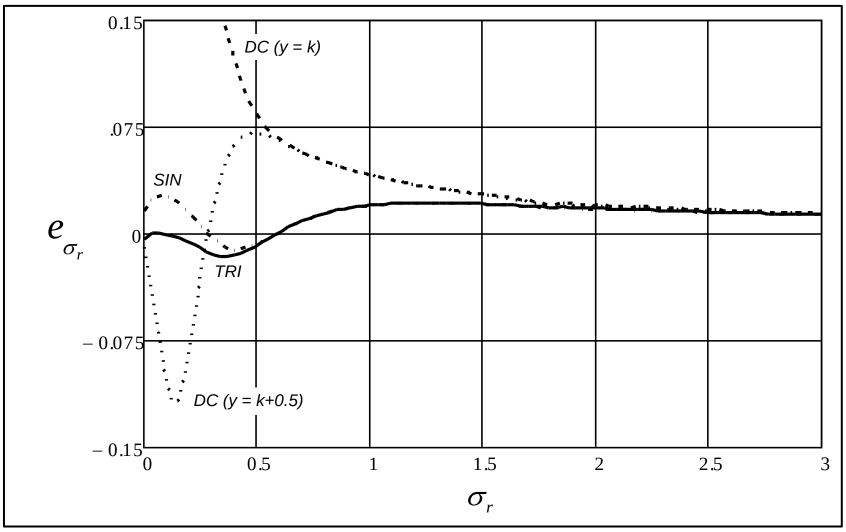

Figure 2: Error of the estimators of the random-noise standard deviation against the actual noise standard deviation, for a DC stimulus (dashed and dotted), a triangular stimulus (solid) and a sinusoidal stimulus (dash-dotted). The two DC curves correspond to a stimulus equal to an ADC transition voltage (dashed) and exactly midway between two consecutive transition voltages (dotted). The triangular and sinusoidal amplitudes are 5 LSB.

4 CONCLUSIONS

This paper has proposed using a sinusoidal stimulus signal to estimate the random-noise standard deviation of an ADC. The resulting estimator is exactly the one recommended by the IEEE 1057 standard for the triangular stimulus. Besides making the test more flexible, this opens the way to combining sine fitting with record alignment so as to dispense with the record triggering that the triangular stimulus requires — in principle removing that source of uncertainty.

STATEMENTS ON COMPLIANCE WITH ETHICAL STANDARDS

Disclosure of conflict of interest

The author declares that there is no conflict of interest.

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