EFFECTIVE ALGORITHMS FOR DYNAMIC QUALITY TESTS OF A/D CONVERTERS USING STEP-WISE APPROXIMATED MULTI-CYCLE SINE WAVE

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Abstract - *When the step-wise approximated multi-cycle sine wave is used as the testing input signal for dynamic quality tests of the A/D converters, the effectiveness, accuracy, and the resolution of the chosen DFT analysis method depends on the proper choice of the method parameters. This paper deals with the theoretical problems of the analysis of the obtained output data of the A/D converter when the above mentioned input signal is applied. The basic principles of effective algorithms are outlined.*

Keywords - A/D converter, dynamic quality test, step-wise approximated sine wave, DFT analysis.

1. INTRODUCTION

Conventional test methods (FFT Test, Sine Wave Curve Fit Test, Histogram Test) standardized in the IEEE Standard for Digitizing Recorders [1], and in the draft of IEEE Std 1241 [2] use the sine wave as the testing input signal. It is recommended to use a generator with the THD (Total Harmonic Distortion) about 10 dB better than the SNR (Signal to Noise Ratio) of the A/D converter under test. However, those methods are not directly applicable in the higher frequency range and for higher resolution (12 - 16 bits) A/D converters, because no commercially available generators with THD less then -100 dB exist.

To overcome the problem, different methods for cleaning the spectrum of the test signals, digital correction methods, and modified FFT methods have been proposed in the literature. As a result the complexity of the test equipment and test environment increases, analysis time becomes longer, number of different test methods modifications increases, thereby complicating the comparison of the gained results.

From the other hand, even if the spectrally pure sine wave is applied, only first six to ten higher harmonics from the output spectrum are used in further calculations to evaluate the ac performance of the A/D converters. This practice leads to the conclusion that the quality of the test signal should be defined in a similar way. In [3] the concept of step-wise approximated multi-cycle sine wave, where only the first six to ten harmonics are kept at low level, was proposed. In this paper the effective algorithms to analyze the recorded data are considered.

2. SIGNAL DESCRIPTION

A step-wise approximated multi-cycle sine wave, consisting of several segments with equal length but variable height (see Fig.1) despite quite rough approximation in the time domain, has relatively sparse frequency spectrum, and suits for dynamic testing of A/D converter, which by nature, is a highly linear device.

The heights of the approximation segment $g_{s,n}$ are calculated according to the formula

$$g_{s.n} = G_0 \sin\left(2\pi\frac{n-1}{k} + \varphi_0\right), \qquad (1)$$

where $n = 1, 2, \ldots k$ is the number of approximation segment, k is the number of segments per cycle, and φ_0 is the initial phase.

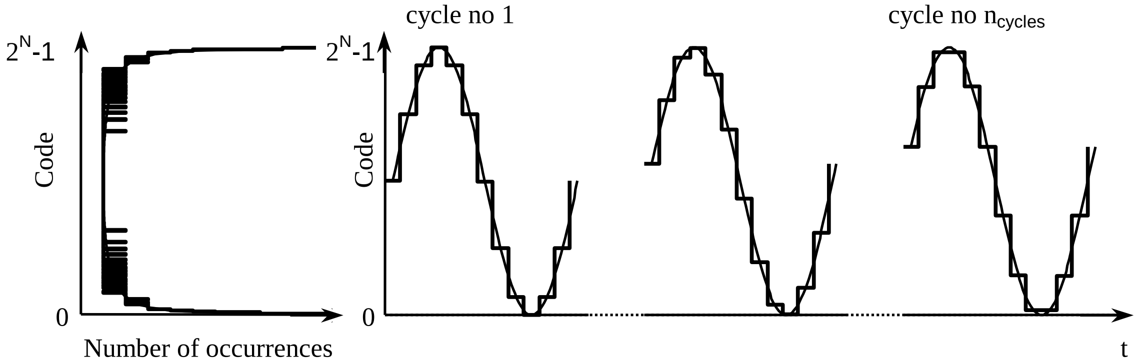


Fig.1 – 12 segment step-wise approximated multi-cycle sine wave for testing of the N-bit AD converter

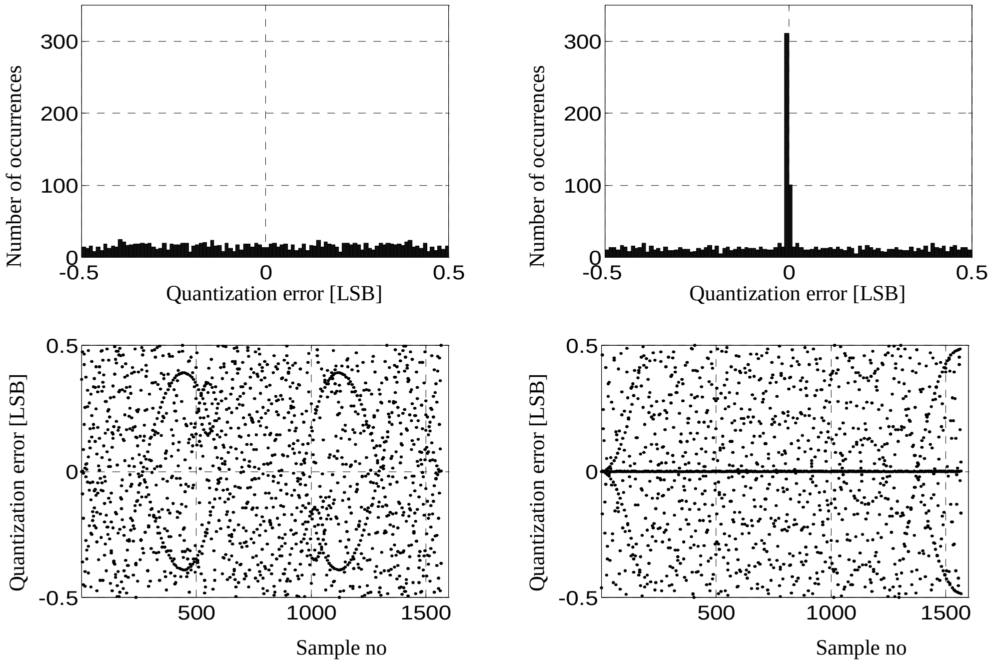
In order to excite all the input codes of the A/D converter the whole multi-cycle test signal consists of the number of k-segment single cycles with slightly (by 1LSB of the A/D converter under test) shifted heights of the segments. The 1LSB differences of sequential single cycles make the test signal almost periodical input signal for the A/D converter.

Number of required single cycles n_{cycles} can be calculated from:

$$n_{cycles} = 2^{N-1} \sin(\pi / k), \tag{2}$$

where N is the number of bits of the AD converter under test.

The calculated multi-cycle test signal can be generated by the high-speed high quality D/A converter, which introduces some quantization error. For conventional sine wave the quantization error is distributed uniformly in the range ±0.5LSB (see Fig.2a). In case of the above described multi-cycle signal the quantization error is also distributed uniformly in the range ±0.5LSB except significant number (about 20%) of values equal to zero (see Fig.2b), which improves by 3 to 5dB the SNR of the generated multi-cycle test signal (see Table 1).



a) b)

Fig.2 – Distribution of the quantization error a) conventional sine wave b) step-wise approximated multi-cycle sine wave (8-segments, 196 cycles)

Table I – Comparison of the quantization errors (expressed as Signal-to-Noise Ratio [dB]) of the step-wise approximated multi-cycle sine wave and the ordinary sine wave, generated by the ideal N-bit D/A converter.

N	Number of approximation segments per cycle, k							Ideal Sine
	8	9	10	11	12	14	16	
8	55.2	53.7	54.1	53.0	53.0	53.0	52.6	49.93
10	66.9	65.3	66.0	64.6	64.8	65.0	64.6	61.97
12	79.2	77.4	77.9	76.8	76.7	77.1	76.8	74.01
14	91.1	89.4	90.0	88.8	88.8	89.1	88.8	86.05

Applying the step-wise approximated sine wave for testing of A/D converters does not change the basis of the conventional test methods because both, the conventional sine wave and the multi cycle test signal will produce similar probability density function (see Fig.1.).

One limiting factor in ordinary test systems is the jitter of the sampling clock the A/D converter, which has strong influence specially at higher frequencies. Even in case, when the input signal of the A/D converter under test is ideal, the jitter phenomenon causes the degradation of the A/D converter performance just only by the non-coherence between the actual sampling time points and how those time points are interpreted by the following digital signal analysis. Conventional way to overcome the jitter effects is by use of an additional high-performance sample-and-hold amplifier (SHA), which improves the high-frequency performance of a even best sampling A/D converter by providing "direct current" signal to the A/D converter. In proposed test method the similar feature is inherently exist, because the output signal of the D/A converter is by definition constant between the transitions (see Fig.3).

3. DYNAMIC PERFORMANCE

The theoretical calculations are based on the assumption that the step-wise approximation is mathematically perfect. Actually the ideal shape of steps is not reachable due to the limiting factors of the components and schematics. Due to the slew limiting effects the step-signals tends to be more

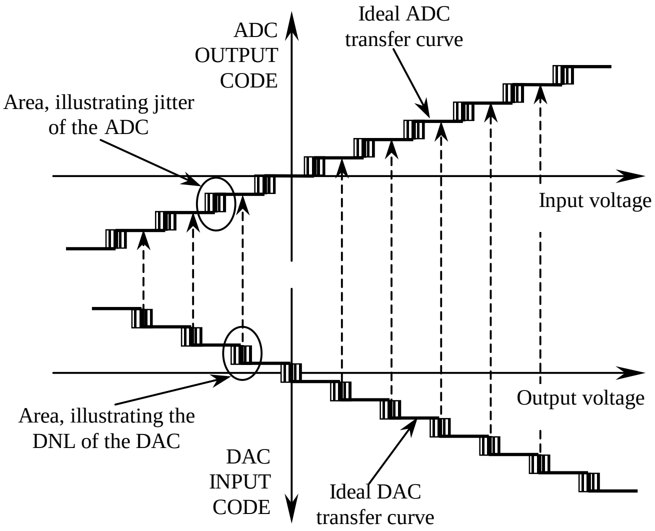


Fig.3 – Interaction of the A/D CONVERETER and DAC in the dynamic A/D CONVERETER test system

trapezoidal and after fast transition edges the over- and undershoots are unavoidable.

The results of analysis are presented in Fig.4, where ideal step-wise approximated sine wave, trapezoidal signal, piece-wise linearly approximated sine wave and the step-wise waveform with glitches are compared. It should be mentioned that the piece-wise linearly approximated sine wave is a special case of the trapezoidal signal and can be also used for testing of the A/D converters. But this signal does not have the constancy of levels, an important feature when minimizing the effects of A/D converter jitter.

From the point of view spectral content the ideal step-wise signal has the highest level of harmonics when comparing to the trapezoidal or piece-wise waveform. As those signals can be derived from the step-wise signal by linear operations, they have the same spectral content but with lowered harmonics levels. Consequently, as far as those physical effects do not produce additional spectral components into the test signal, they are acceptable as a kind of smoothing filter.

Another problem is related to the existing glitches at the output of the D/A converter. Those uncontrolled movements of the D/A converter output during a transition can arise mainly from two mechanisms: capacitive coupling of digital transitions to the analog output, and the timing differences of D/A converter switches.

Those glitches will produce both out-of-band and in-band harmonics when the D/A converter is reconstructing a digitally generated sine wave (see Fig.4d). In dynamic A/D converter test systems it is important that the level of in-band harmonics will remain at least 10dB lower than the expected harmonic level of the tested A/D converter. Review of the manufacturers data sheets shows the availability of suitable high-speed high quality D/A converters. The 10-bit low-glitch D/A converters with sampling rate of 150-200MSPS, slew rate of 450V/μs, and glitch impulse area of about 5pVs will produce about 50mV glitches at 0.5 full scale transitions. According to Fig.4d the in-band harmonics level are still low

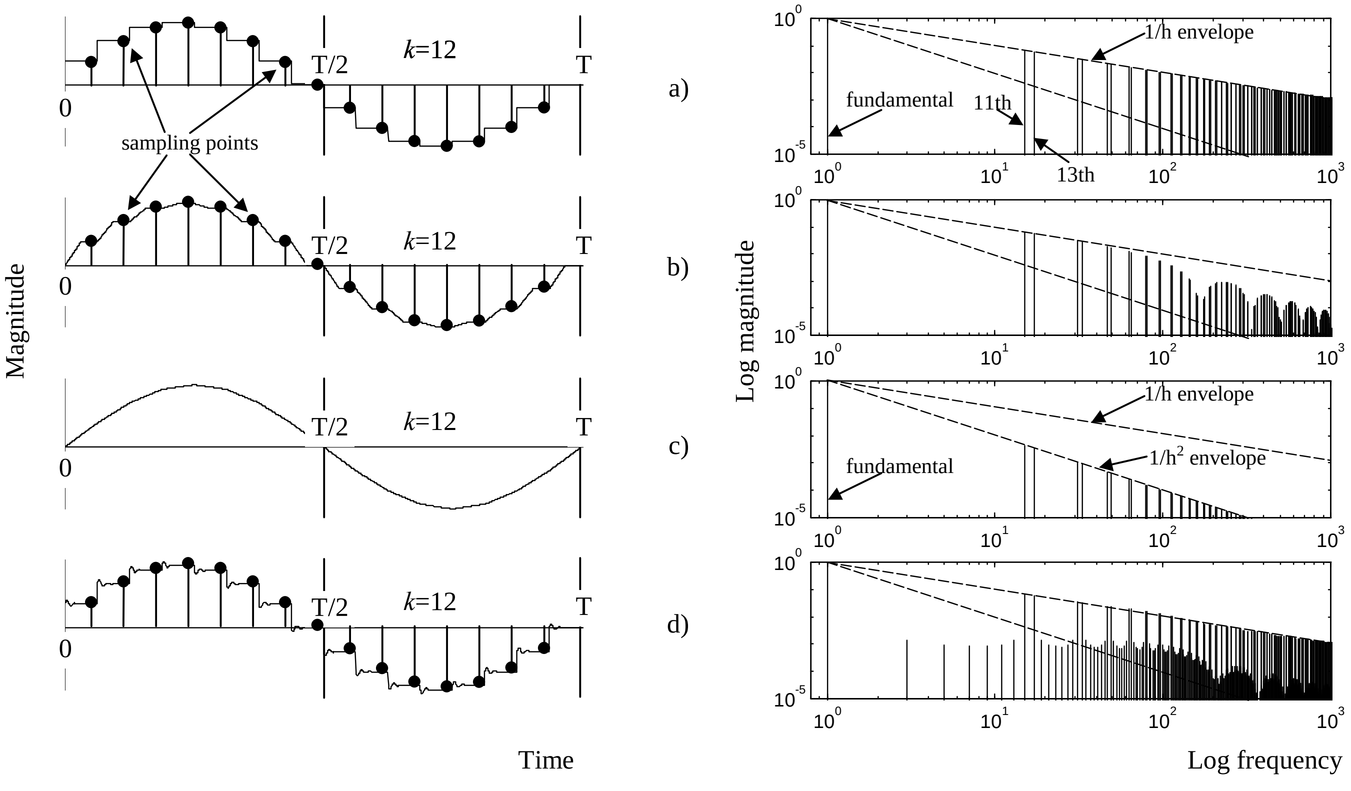


Fig.4 – Waveforms and the spectra: a) step-wise approximated sine wave, b) trapezoidal approximated sine-wave, c) piece-wise linearly approximated sine wave, d) step-wise approximated sine-wave distorted by glitches

enough for testing of the high quality A/D converters.

When considering the quality of the test signals for testing of A/D converters it is reasonable to distinguish two meanings of the spectrum content.

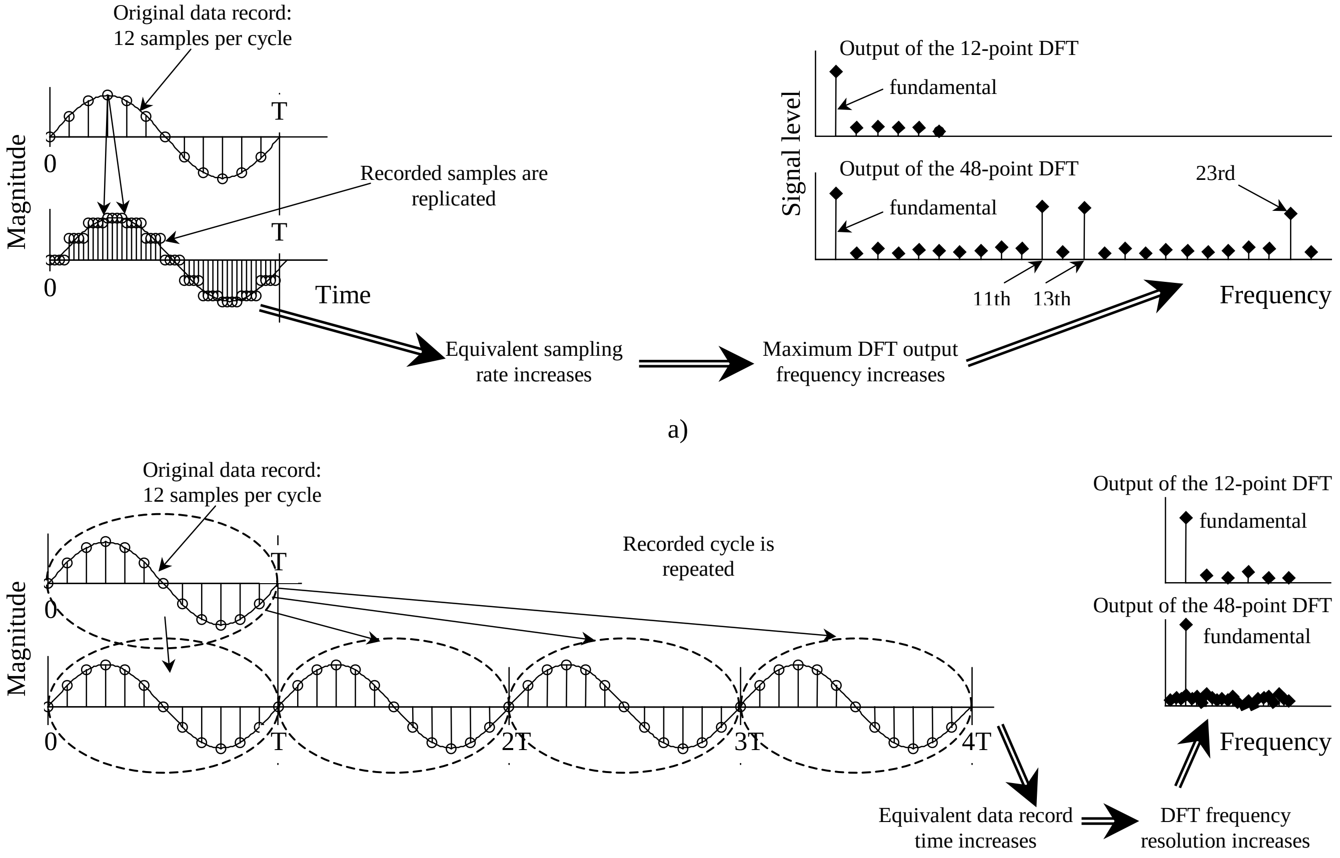
First, mathematically the spectrum content of the input signal does not have direct influence on the parameters of the A/D converter under test, because data record is obtained not continuously but at discrete time moments. These moments can be chosen so, that the transition components at the output of the D/A converter are avoided and the output levels of the D/A converter are stabilized at the pre-calculated values corresponding to the values of sine wave at those discrete time moments. As shown in Fig.4, the time delay up to one clock cycle is introduced during which the D/A converter output stabilizes. In this application the step-wise waveform is identical to the ideal sine wave, which means that all the higher harmonics observed at the output of the A/D converter are caused only by the A/D converter itself (non-idealities of the transfer curve, jitter, etc.). Mathematically the actual spectrum content of the step-wise waveform is not taken into account.

In reality the form of the test signal has influence on the performance of A/D converter, but this is indirect. The fast edges and glitches of the step-wise waveform will force A/D converter to operate in the slew-limiting mode. The analysis shows, that more important than the actual shape of the test signal is that the test signal has "right" value at "right" moment. Consequently, all kinds of filtering and smoothing operations are allowed as far as they do not disturb the pre-calculated steady state value of the test signal.

The step-wise waveform alone does not exhibit better performance than the continuous sine wave, the full benefit can be obtained by applying of the whole proposed testing algorithm and testing chain. The disadvantage of described method is that the fast transitions of the step-wise approximated sine wave will cause additional effects missing in the ordinary sine wave testing method. Advantages of the proposed chain are the simplicity of reconfiguring and the elimination of the jitter of the A/D converter from the dynamic testing process. This feature allows to perform more selective measurements for characterization of the A/D converters, for example to separate the effects of the non-linearity of the transfer curve and the jitter, both degrading the A/D converter performance.

4. DESCRIPTION OF ALGORITHMS

Once the test data record is obtained, it is usually analyzed by a DFT analysis method. Instant analysis of the recorded raw data is possible, but the continuous phase shift, accompanied with the described test signal complicates the interpretation of the DFT output.



a)

b)

Fig.5 – The effectiveness of the proposed algorithms are obtained by the combination of the replication and repeating of the sampled data.

In proposed method every single cycle meets the endpoint discontinuity requirement put by non-windowed DFT analysis. Therefore all single cycles can be analyzed separately and afterwards the results of the several DFT can be averaged.

The problem is that the number of samples per single cycle is very low (about 8 to 16 as shown above). At the few-point DFT output the magnitudes of the frequency bins in the vicinity of half sampling frequency are erroneous (the DFT calculates up to 60% higher values than actual). Therefore the direct applying of the 8 to 16-point DFT results in a low evaluating accuracy of the spectrum components and consequently the characteristics of the A/D converter as well.

But in our case, where the whole testing chain from the generation of the test signal to the AD sampling procedure and data analysis is synchronous, some regrouping and reshaping of the recorded raw data allows easily to increase the resolution of the DFT and therefore the accuracy of the obtained results. It is important to remind that regrouping and reshaping of the recorded data do not generate any new information; the idea is to extract the existing information from the raw measurement data.

In Fig.5 the 12-segment step-wise approximated multi-cycle sine wave is used as an example to explain two different reshaping methods. In both cases the number of points to be feed to the DFT analysis increases, allowing artificially to increase the maximum frequency and the frequency resolution of the DFT output.

In first method (see Fig.5a) every sample point of the single cycle is replicated K times. K can have any value greater than one. In practice the actual value of K depends on required accuracy of estimating higher harmonics and different test set-up requirements. According to the analysis the higher harmonics estimation error of 1% for the 8 to 16-segment approximated sine wave can be achieved at $K > 10$. In order to keep consistent the DFT frequency information data the signal period T should be kept constant during replicating process. As the signal period is unchanged and the number of samples per period increases, the equivalent sampling rate also increases by factor of K. Sampling rate defines the maximum DFT output frequency and therefore the maximum frequency of the DFT output also increases.

Even the conventional A/D converter parameter estimation methods use only first six to ten higher harmonics, the calculation of other higher harmonics are necessary in order to increase the accuracy of the few-point DFT.

In second method (see Fig.5b) the whole acquired single cycle is repeated K times. As the period T of the single cycle should be kept unchanged in repeating process, the equivalent record time and consequently the DFT frequency resolution increases.

Both of those independent methods can be combined in different ways in order to find the optimal solution for each particular test task.

5. CONCLUSIONS

The accuracy and resolution of the described algorithms are easily controllable by the replicating and repeating procedures.

The simple analysis algorithm of generating the step-wise approximated multi-cycle sine wave and corresponding DFT analysis methods allow to generate simple test signal and analysis algorithm for each particular test task. This is valid also for other type of test signals like ramp or triangular wave.

The proposed test methods are applicable without changes in the future, when the development in technology results in an increased performance of the A/D converter and D/A converter. Only some minor changes in the sampling rate/update rate related circuitry could be foreseen.

The described test signals and analysis algorithms suits well for most common statistical test methods and for time and frequency domain test methods.

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