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STEP-WISE APPROXIMATED MULTI-CYCLE SINE WAVE FOR DYNAMIC QUALITY TESTS OF AD CONVERTERS

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Abstract: For dynamic quality tests of the AD converters a high quality test signal is required. When testing a high speed AD converters, the conventional test signals have reached their dynamic and resolution limits. In this paper an overview of using the step-wise approximated multi-cycle sine wave as a test signal for dynamic quality tests of high speed, high quality AD converters is presented. The proposed test signal is characterised by high stability time and amplitude parameters. The slight difference in the heights of steps of the sequential single cycles ensures stimulation of all codes of the AD converter. Basic rules for increasing the accuracy of the spectrum component evaluation by FFT analysis are considered.

Keywords: AD converter, dynamic quality test, step-wise approximation.

1 INTRODUCTION

The dynamic performance of AD converters can be analyzed by several methods in time [1] and frequency [2] domains and by statistical analysis [3] as, for example, sine wave curve fit test, spectral test, and histogram test.

A useful way to evaluate the ac performance of AD converters is to extract from those tests the Signal-to-Noise Plus Distortion S/(N+D) or equivalent, Effective Number of Bits ENOB versus input frequency characteristics. Those characteristics are somewhat all-inclusive including effects of both noise and distortion. Typically, a spectrally pure sine wave excitation signal is being used in all these tests. But for high speed, high quality AD converters the conventional test signals have reached their dynamic and resolution limits. In this paper the basic principles of highly stable test signal with controllable spectral purity is proposed.

Generally, for testing highly linear devices like A/D converters a test signal should have parameters exceeding several times the quality of A/D converter performance. Usually a pure sine wave is being used for dynamic testing of A/D converters, where first six to ten higher harmonics are used in further calculations. This practice leads evidently to the conclusion that the quality of the test signal should be defined in a similar way. It is important to keep low the level of the first six to ten higher harmonics; the actual values of the rest harmonics are not critical for testing of AD converters. This is the main criterion for designing test signals that do not have pure spectrum.

This statement allows to consider the test signal as a special kind of multitone signal. As the AD converter is highly linear device, the higher order nonlinearity and intermodulation components due to the input multitone signals can be neglected.

2 TEST SIGNAL DESCRIPTION

The idea bases on generating a test signal with few fixed, easily controllable and stable levels per period. When the heights of the levels are chosen in a proper way, a clean spectrum in the region of interest is achievable.

A step-wise approximated sine wave, which consists of several segments with equal length but variable height, has such a spectrum [4]. Despite quite rough approximation in the time domain, the corresponding spectrum is relatively sparse. For example, a step-wise approximated sine wave with only 12 approximation segments k = 12 does not contain higher order harmonics up to the 11th (see Figure 1).

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, …k is the number of approximation segment and φ_0 is the initial phase.

The numbers of the higher harmonics h, existing in the spectra can be found by the simple formula:

$$h = k \cdot i \pm 1, \qquad (2)$$

where i = 1, 2, 3, …, and the magnitudes of those harmonics are inversely proportional to the number of the harmonics h (see Figure 1).

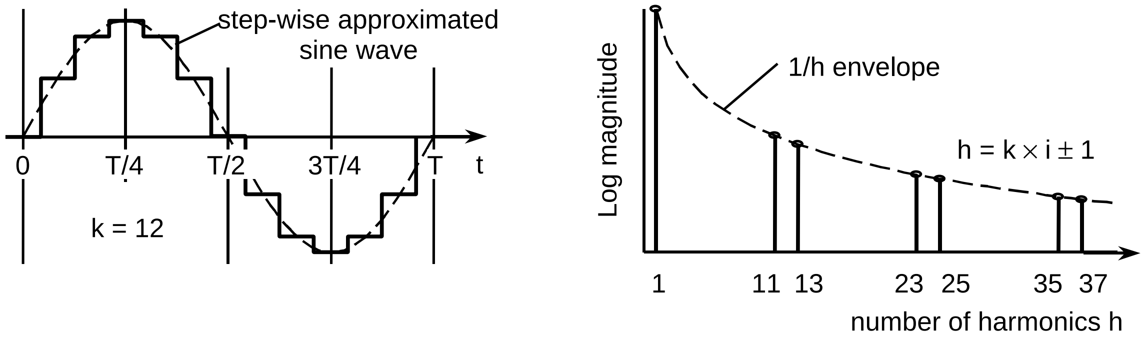

Figure 1. Waveform and the spectrum of the step-wise approximated sine wave

The described signal is not directly applicable for testing of A/D converters, because the step-wise signal stimulates only a few input codes of the A/D converter (altogether 12 in case of k = 12 segment approximation). To overcome this obstacle, the entire test signal should contain more segments with all possible heights of steps.

This kind of signal can be easily designed by appending several slightly different step-wise approximated sine wave cycles into a one, multi-cycle signal. To excite all codes of the AD converter it is reasonable to alter the heights exactly by one LSB of the AD converter under test. Number of the required single cycles n_{cycles} to cover all the AD converter input codes can be then calculated from the formula:

$$n_{cycles} = 2^{N-1} \sin(\pi / k), \qquad (3)$$

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

As the number of cycles should be integer, the value of n_{cycles} is rounded towards infinity (see Table 1). To meet special requirements raised by practical test tasks, the actual number of cycles per data record may vary.

Table 1. Minimum number of single cycles of the multi-cycle test signal to cover all input codes of the AD converter

N	Number of approximation segments per cycle, k						
	8	10	12	14	16	18	20
8	49	40	34	29	25	23	21
10	196	159	133	114	100	89	81
12	784	633	531	456	400	356	321
14	3135	2532	2121	1823	1599	1423	1282
16	12540	10126	8481	7292	6393	5691	5127

The entire 12-segment multi-cycle test signal for testing of the 8-bit AD converter is shown on Fig.2. Please note that every single cycle meets the endpoint discontinuity requirement put by non-windowed FFT analysis. The 1LSB differences in the heights of segments of sequential single cycles make the test signal almost periodical signal. This simplification is valid for the AD converter, but not adequate for FFT analysis, where continuous phase shift causes the modulation components in the signal spectra and should be avoided in order to have easily understandable analysis results.

The heights of segments of the sequential single cycles of the entire multi-cycle test signal can be calculated from the generic formula (1) by sweeping the initial phase φ_0 over certain range, defined by the parameters N and k. The values of the initial phase $\varphi_{0,i}$, ensuring minimum number of cycles to cover all the AD converter input codes can be calculated from:

$$\varphi_{0,i} = \arcsin\left(\frac{i}{2^{N-1}}\right), \tag{4}$$

where i = 1, 2, … n_{cycles}.

Applying the step-wise approximated sine wave for testing of AD converters does not change the basis of the conventional test methods, because when applied to the perfect AD converter, both the conventional sine wave and new proposed test signal will produce similar probability density function, PDF (see Fig.2.).

For a sine wave input, a perfect AD converter will produce a probability density function p(V):

$$p(V) = \frac{1}{\pi\sqrt{A^2 - V^2}}, \tag{5}$$

where p(V) is the probability of an occurrence at voltage V, and A is the peak value of the sine wave.

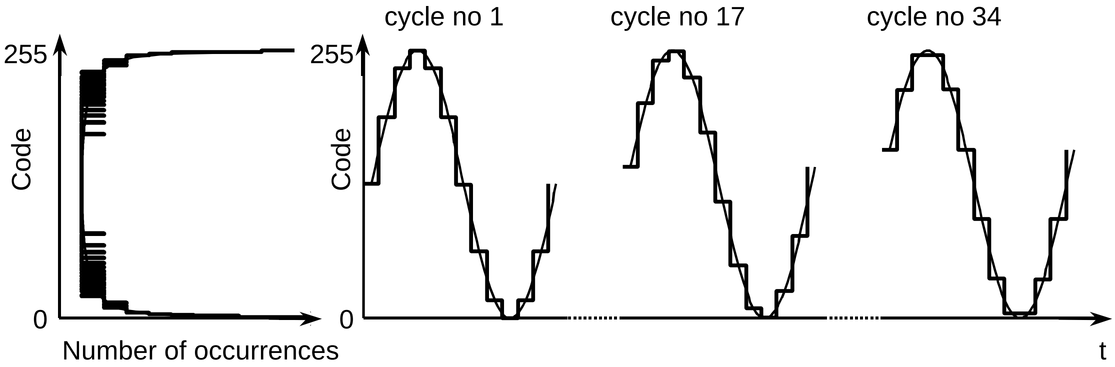

Figure 2. 12 segment step-wise approximated multi-cycle sine wave for testing of the 8-bit AD converter

3 SAMPLED DATA ANALYSIS

As the whole testing chain is fully synchronous, exact timing between the updating moment of the DA converter and the sampling point of AD converter is simply achievable. Time delay up to one clock cycle is needed to introduce, during which the transient processes at the output of the DA converter are ended and a stable signal is present at the input of the AD converter under test. The clock jitter, aperture delay, and aperture jitter of the DA converter and AD converter should be also taken into account.

Once the data record is obtained, it can be analyzed in a number of ways, usually by applying a FFT analysis method, which takes a discrete number of samples, M, and converts them into M/2 discrete spectral components. Instant analysis of the recorded raw data is possible, but due to the phase modulation effects, accompanied with the proposed test signal, interpretation of the FFT output may be complicated. In our case, where the whole testing chain from the generation of the test signal to the AD sampling procedure are synchronous, some regrouping and reshaping of the recorded raw data will allow to increase the resolution of the FFT and therefore the accuracy of the obtained results.

All single cycles can be analysed separately and afterwards the results of the several FFT can be averaged. The single cycles of the entire test signal are designed to meet the endpoint discontinuity requirements and are therefore well suited for direct FFT analysis without applying preceding windowing procedure. But, as the described methods are intended for testing of the high speed AD converters at high frequency input signal, available number of samples per single cycle decays equal to the number of segments per cycle (about 8 to 16 as shown above). Therefore direct applying of the FFT results in a low evaluating accuracy of the signal spectra and the characteristics of the AD converters.

For example, if the f=1MHz, T=1μs signal is sampled by the f_s=8MHz sampling frequency during record time t=1μs, an $M=f_s \times t=8$ samples long data record is collected. When applying M-point FFT directly to the recorded data, then according to the main properties of the FFT the maximum frequency component f_{max} in the output spectrum of the FFT is $f_{max}=f_s/2=4$MHz and the frequency resolution Δf is $\Delta f=f_s/M=1$MHz. This is obviously insufficient for calculating the SNR or ENOB of the AD converter at the input frequency 1MHz, where at least first six higher harmonics at frequencies f_H = 1, 2, 3, 4, 5, and 6MHz should be taken into account. Another problem is the above mentioned low accuracy of evaluation of the spectrum components, when a few point FFT is used. The simulations show that the evaluation error of the existing higher harmonics (see equation (2)) may reach up to the 60%.

Regrouping and reshaping of the sampled data prior FFT analysis can increase the accuracy of the spectrum component evaluation. There are two principal ways to reshape the recorded data. First is to replicate K times every sample point of the single cycle, and the second is to repeat K times the whole acquired single cycle. In both cases the number of points to be feed to the FFT analysis increases, allowing artificially to increase the maximum frequency of the FFT spectrum, and the frequency resolution of the FFT respectively. In order to keep coherent the frequency of the actual input signal of the AD converter and the results from the analysis of reshaped data the period T of the single cycle should be kept unchanged in reshaping processes. This is equivalent with the increased sampling rate in the first case and with the increased record time in the second case.

For example, replicating K times every sample of the original 8-sample long data record of the single cycle, results in a reshaped data record of $M=K\times 8$ points. As the period of the single cycle $T=1\mu s$ is unchanged, the equivalent sampling rate $f_{s,eqv}=M/T=f_s\times K$ is artificially increased K times and consequently the maximum frequency component of the FFT output $f_{max}=f_{s,eqv}/2$ as well. Repeating K times the whole single cycle yields also in a data record of $M=K\times 8$ points keeping the period T of the single cycle unchanged, the equivalent record time $t_{eqv}=t\times K$ increases K times and the frequency resolution $\Delta f=f_S/M$ as well.

The simulations show, that for the 8 to 16 segment approximations the estimation error of 1% can be achieved at K = 6…11. The actual value of K depends on many circumstances put by specific test set-up requirements.

4 CONCLUSIONS

Calculated according to the presented algorithm and generated by the high speed, high quality DA converter the step-wise approximated multi-cycle sine wave test signal has several excellent features:

1. Applying the described test signal for the dynamic test of the AD converters, two usually conflicting requirements can be fulfilled. First, the AD converter is excited by the high frequency input signal and second, the quality of the input signal is high enough for testing of the AD converter at its nominal number of bits.
2. The duration of the single cycle segment can be chosen equal to the sampling period of the AD converter under test, therefore the frequency of the test signal is relatively high, reaching up to about 1/8 of f_s without losing spectral purity and amplitude precision.
3. Each single cycle is generated to meet the end point discontinuity requirement from FFT analysis. It discards the windowing procedure before FFT analysis and allows regrouping and reshaping of the recorded data in order to control the parameters of the FFT.
4. The complete multi-cycle sine wave ensures the same probability density function of the AD converter output code as a conventional sine wave test signal.
5. The described test signal suits well for most common statistical test methods and for time and frequency domain test methods.
6. The simple algorithm allows to generate an optimal test signal for each particular test task.

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