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PIECEWISE LINEARLY APPROXIMATED SINE WAVE FOR DYNAMIC QUALITY TESTS OF A/D CONVERTERS

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Abstract. An overview of using the piecewise linearly approximated sine wave as a test signal for dynamic quality tests of A/D converters is presented. The basic principles and generation methods of a specific test signal for A/D converters are explained. A comparison of the classical sine wave, proposed test signal, and triangular wave is presented. Suitability of the piecewise linearly approximated sine wave for dynamic quality tests of A/D converters in time and frequency domain and for statistical methods is considered.

Key words: A/D converter, dynamic quality test, spectral test, histogram test, sine wave, wave approximation.

1. INTRODUCTION

The dynamic performance of A/D converters can be analysed by several methods in time [1] and frequency [2] domains and by statistical analysis [3] as, for example, the sine wave curve fit test, spectral test, and histogram test. Typically, a spectrally pure sine wave excitation signal is being used in all these tests. However, several problems arise when high-precision high-speed A/D converters have to be tested.

Let us consider some drawbacks of the application of the sine wave excitation.

1. The purest sine wave is achievable by using a high resolution D/A converter (e.g., 20 bit). A large number of samples per period is needed and therefore only up to 100 kHz sine waves can be synthesized [4]. At higher frequencies, a smaller number of samples is available resulting in higher level of harmonics in the test signal.

2. Bellan, Brandolini et al [5] have shown that the sine wave, due to its variable slope, does not stimulate uniformly the A/D converter transition levels. Consequently, a transition level displacement with respect to the ideal value, integral nonlinearity error, results in an increase in the quantization error power that depends on its location on the transfer characteristic.

3. By histogram tests, the sine wave gives a substantially non-flat probability density function (PDF) and therefore the test errors are different in different positions.

Generation of high quality test signals with well-controlled level and time properties has played a vital role in all testing areas. Usually the requirements for stability and spectral purity cannot be met simultaneously. The result is that spectrally pure sine wave sources have low magnitude and frequency stability due to the high Q value frequency selective circuits. On the other hand, the highly stable signals have poor spectral purity.

2. TEST SIGNALS

For testing highly linear devices like A/D converters, a test signal should have parameters exceeding several times the quality of the A/D converter performance. Usually a pure sine wave is used for testing of the A/D converters, but for linearity test it is sufficient when six to nine higher harmonics are taken into account. This is the main criterion for designing test signals that do not have an infinitely pure spectrum. It is important to keep low the level of the first six to nine higher harmonics; the actual values of the other harmonics are not critical.

A stepwise approximated sine wave has such a spectrum as shown by Min and Parve [6]. Despite the quite rough approximation in the time domain (Fig. 1), the corresponding spectrum is relatively sparse. For example, a stepwise approximated sine wave with only three approximation levels ($m = 3$) does not contain higher order harmonics up to the 11th (Fig. 2). When the values of the approximation levels g_q are calculated according to the formula

$$g_q = G_0 \sin\left[\frac{\pi}{4m}(2q-1)+\varphi_0\right], \tag{1}$$

where $q = 1, 2, \ldots, m$ is the number of the approximation level and φ_0 is the initial phase, then the numbers of the higher harmonics (h), which exist in the spectra, can be found from simple formula

$$h = 4mi \pm 1, \tag{2}$$

where $i = 1, 2, 3, \ldots$.

The magnitudes of these harmonics are inversely proportional to the numbers of the harmonics (Fig. 2).

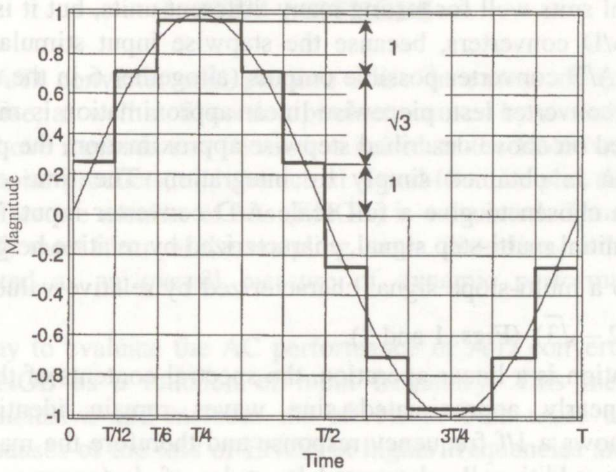

Fig. 1. Stepwise approximated sine wave.

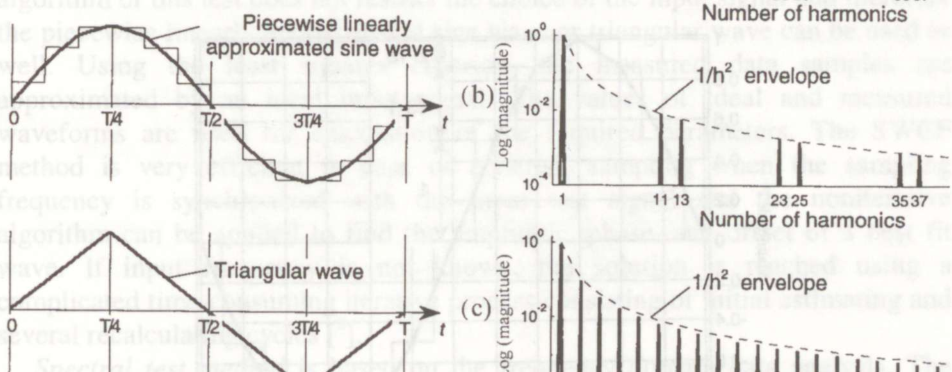

Fig. 2. Waveforms and the spectra: a) stepwise approximated sine wave, b) piecewise linearly approximated sine wave, c) the ordinary triangular wave.

This signal suits well for testing many different units, but it is not applicable for testing A/D converters, because the stepwise input stimulates only a few codes of the A/D converter possible outputs (altogether 6 in the case of $m = 3$). For the A/D converter test, piecewise linear approximation is more appropriate (Fig. 3). Based on above described stepwise approximation, the piecewise linear approximation is obtained simply by integration. The time constant of the integration is chosen to give a full scale A/D converter input. The integration converts an initial multi-step signal, characterized by relative heights of the steps $1:\sqrt{3}:1$, into a multi-slope signal characterized by relative values of the slopes $1:(\sqrt{3}-1):(2-\sqrt{3})$ (Figs. 1 and 3).

As integration is a linear operation, the spectral contents of the stepwise and piecewise linearly approximated sine waves remain identical. However, integration shows a 1/f frequency response and therefore the magnitudes of the harmonics are additionally decreased by order of h (compare corresponding spectra in Figs. 2a and 2b).

The benefit from applying the integration is twofold:

1) integration of the stepwise approximated sine wave adds additional 20 dB decrease of the spectrum components for every decade of the frequency, reducing in this way the power of the existing higher harmonics;

2) integration converts the stepwise approximated sine wave into a piecewise linearly approximated sine wave, more suitable for the dynamic test of A/D converters.

At higher frequencies, when the direct digital synthesis reaches its dynamic and resolution limits, the analogue integration seems to be an acceptable method for high quality signal generation [7].

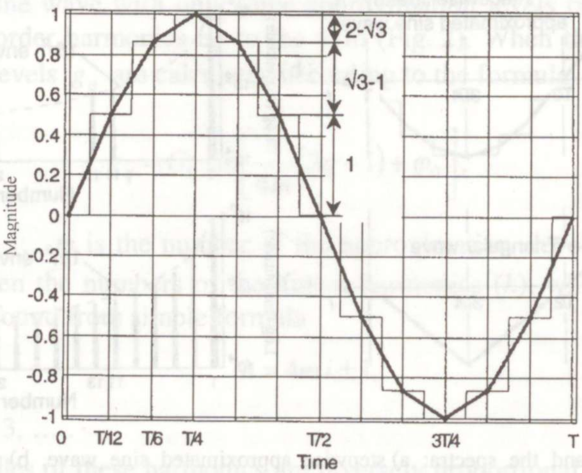

Fig. 3. Piecewise linearly approximated sine wave.

3. TEST METHODS

An actual A/D converter will produce noise in excess of the theoretical quantization noise, as well as distortion products caused by a nonlinear transfer function. All above methods can be used to calculate the RMS value of all the distortion and noise products, and the actual signal-to-noise plus distortion ratio (S/(N+D)) or effective number of bits (ENOB) is calculated. Those parameters globally quantify most forms of the sampling errors, distortion, and system noise and are accepted as an overall measure of dynamic performance of A/D converters.

A useful way to evaluate the AC performance of A/D converters is to plot S/(N+D) or ENOB as a function of input frequency. This measurement is somewhat all-inclusive and includes the effects of both noise and distortion products. The causes of the loss of ENOB at higher frequencies are varied. The linearity of the A/D converter transfer function degrades as the input frequency increases, thereby causing higher levels of distortion. Another reason why the ENOB of the A/D converter decreases with input frequency is that the phase jitter of the sampling clock of the A/D converter causes a voltage error which is a function of the slew rate and results in an overall degradation in ENOB.

The triangular and piecewise linearly approximated sine wave can be interpreted as a kind of multitone signals and therefore one has to take into account a possible intermodulation effect in the A/D converter, inherently missing in case of the sinusoidal test signal. For that reason it is preferable to use the piecewise linear approximation sine wave instead of the triangular wave, ensuring considerably smaller intermodulation products in the spectrum of the output signal of the A/D converter.

Sine wave curve fit test (SWCF) is performed in the time domain. The algorithm of this test does not restrict the choice of the input signal and therefore the piecewise linearly approximated sine wave or triangular wave can be used as well. Using the least squares criterion, the measured data samples are approximated by an ideal input signal. The values of ideal and measured waveforms are used for calculation of the required parameters. The SWCF method is very efficient in case of coherent sampling when the sampling frequency is synchronized with the input test signal and the noniterative algorithm can be applied to find the amplitude, phase, and offset of a best fit wave. If input frequency is not known, the solution is reached using a complicated time-consuming iterative process consisting of initial estimating and several recalculating cycles [8].

Spectral test method is based on the frequency domain data analysis. The input signal is sampled at regular intervals and the discrete Fourier transform of the samples is computed with a fast Fourier transform (FFT) algorithm.

In the case of non-coherent sampling, a windowing procedure should be applied to reduce the leakage effect. To avoid the problems connected with the windowing, a new data record with exact number of periods can be built by interpolating and re-sampling the recorded data before executing FFT.

Commonly, the FFT method is considered to be more efficient than the SWCF.

In *histogram test* an estimation of the PDF of the output code is calculated. It is compared with the theoretical PDF of the applied input signal and the results of the histogram are used to extract the required parameters.

A very large number of samples are required to build an accurate statistical picture of each code width. If the number of samples is inadequate for high statistical confidence, the result will look considerably worse than the actual performance of the A/D converter.

The results of the comparative study of three different signals for histogram test purposes are shown in Fig. 4. Here the ideal 10-bit A/D converter is used to take a 100,000 sample record. As one can see, the curve, corresponding to the sine wave, scales out from the chosen y-axis limits. Altogether the number of occurrences of the 32 boundary output codes of the A/D converter are more than 250 and reaching up to 1723, while the minimum number of the samples per code is 62.

In case of the piecewise linearly approximated sine wave, the difference of the maximum and minimum number of occurrences is roughly fourfold. The ideal signal for the histogram test is certainly the triangular wave but the piecewise linearly approximated sine wave gives also reasonable results.

The major problem of the code density method, used in the evaluation of the A/D converter performance, concerns the large number of samples needed to estimate the parameters with an acceptable confidence level.

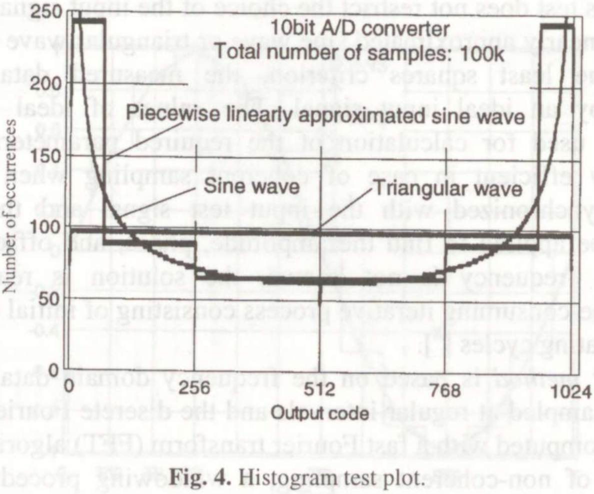

Fig. 4. Histogram test plot.

4. CONCLUSIONS

The knowledge of the dynamic behavior of high-precision high-speed A/D is of great importance for estimating the measurement errors. The quality of the test signal for evaluation of the dynamic performance of the A/D converters should be considerably higher in comparison with the corresponding parameters of the A/D converter. Conventional digital and analogue signal generation methods have reached their dynamic and resolution limits and, therefore, an attempt is made to generate a test signal with high stability and controllable spectral purity.

The proposed piecewise linearly approximated sine wave can be characterized by increased dynamic parameters, good stability, and simplicity of generation. It fits adequately for most of the time and frequency domain tests, as well as for the statistical test.

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TÜKITI LINEAARSELT APROKSIMEERITUD SIINUSSIGNAAL A/D-MUUNDURITE DÜNAAMILISEKS TESTIMISEKS

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On põhjendatud uute testsignaalide kasutamist ülitäpsete ja kiiretoimeliste A/D-muundurite dünaamilisel testimisel. On esitatud tükiti lineaarselt aproksimeeritud siinussignaali genereerimise alused ja kirjeldatud signaali genereerimise võimalikke meetodeid. Sellisel testsignaalil on eelised tavalise siinussignaaliga võrreldes ning see on sobiv A/D-muundurite dünaamilise testimise meetodite enamiku puhul.