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Frequency Domain analysis of ADCs in IEEE-1241 and DYNAD:
A comparison

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Introduction

With the introduction of integrated circuits after the transistor invention by Shockley back in the early 60’ies, no one expected to find a computer assisting in doing your laundry, or keeping track if your milk has gone bad. Since computers are digital systems, and the world is analog, the interface between the two is becoming more numerous. In order for the electronics to keep reaching the mass markets of the world, cheap and power efficient Analog-to-Digital-Converters or ADCs are essential. As more companies are developing ADCs, the needs to find an effective way to communicate the performance in a unique way gain importance. This would reduce the time needed for the buyers of ADCs to validate the performance of their products. This is where a standardized procedure to quantify to performance of a device is introduced. There are three main international standardization bodies, which compose the legally committing standards. In addition to these bodies, there are professional associations that also compose recommendations for the members. Two examples of such organizations are the IEEE Instrumentation and Measurement Society and the European project DYNAD. In this report, the IEEE-1241 standard specifying recommendations of ADC measurements are compared to the same recommendations given by the DYNAD standard.

Objective

The objective of the summer school project was:

1. To compare the IEEE 1241 and the DYNAD standards on how they described the measurement methods to determine:
   - THD
   - SFDR
   - ENOB
   - SNHR
   - SINAD

2. For these definitions, an Automatic Test Environment (ATE) should be developed in LabView, which should present the results of the measurements in an easily readable format.
3. The work should also result in a comparison of the two standards, from readability, easiness of use, completeness, and effectiveness.

4. In doing this, the student groups also gained many "Soft" skills, such as LabView, team work with other EU cultures, and English communication.

**IEEE-1057 (IEEE Standard for Digitizing Waveform Recorders)**

This standard was issued in 1999. It covers Digitizing recorders, and is more general than the IEEE-1241. Both of the standards are written by the Instrument and Measurement Society of IEEE.


This standard has been around since 2000, and is currently under revision. The issuing society is TC-10, which is a part of the Instrumentation and Measurement Society.
This standard is more specific towards ADC measurements.

**DYNAD (Dynamic Testing for Analog-to-Digital Converters using Sine-waves)**

This is an EU approach to define an ADC measurement standard. This is to cover more of the aspects of the measurements, and is more detailed.
Analysis of the standards

Differences between the IEEE and DYNAD

General differences:

- The IEEE-1241 Standard evaluates the whole spectrum from $-f_s/2$ to the $f_s/2$, where $f_s$ is the sampling frequency. DYNAD use only the positive frequencies.

- The above parameters are calculated from an averaged spectrum in the IEEE-1241 standard:

$$X_{avm}[f_m] = \frac{1}{K} \sum_{k=1}^{K} |X_k[f_m]| \quad m = 0, 1, \ldots, M - 1$$

This is used because it has a smaller variance than the non-averaged spectral magnitude, $X_k$. But the DYNAD does not apply averaged spectrum except SFDR, where

$$|Y_{avm}[k]|^2 = \frac{1}{R} \sum_{i=1}^{R} |Y_i[k]|^2$$

So, the variance of some parameters of DYNAD will be bigger.

- In the IEEE-1241 Standard, the considered parameters

- Since the considered parameters are generally depend on both the amplitude and the frequency of the input signal the IEEE standard says they shall be specified. The DYNAD does not.

- In case of coherent sampling both standards give more or less the same results. For non-coherent sampling, the DYNAD and the IEEE standards give different solutions. Both standards propose windowing. The IEEE-1241 does not specify which window function that should be used for non-coherent sampling, whereas the DYNAD specifies which window should be used for which resolution of the ADC. Moreover, the DYNAD specifies for all the different parameters how the window functions should be used for all the measured entities.
Total Harmonic Distortion (THD):

Total Harmonic Distortion (THD) is the ratio of the sum of the squares of all harmonics including their aliases to the rms power of the fundamental component.

**IEEE-1241:**

\[
\text{THD} = \frac{1}{M} \sqrt{\sum_{h} (X_{avm}(f_h))^2}
\]

THD is also expressed in dB

\[
\text{THD}_{dB} = 20 \log_{10} \left( \frac{\text{THD}}{A_{rms}} \right)
\]

\[
A_{rms} = \frac{1}{M} \sqrt{(X_{avm}(f_i))^2 + (X_{avm}(f_s - f_i))^2}
\]

**DYNAD:**

\[
\text{THD}_{dB} = 10 \log \left( \frac{\sum_{h=2}^{h_{max}} |Y[h,J]|^2}{|Y[J]|^2} \right)
\]

- The members of the set harmonics \((f_h)\) must be specified. If not specified, the second through the tenth harmonics are applied.
- The two THD\(_{dB}\) give more or less the same results.

**Spurious Free Dynamic Range (SFDR):**

SFDR is the ratio of the amplitude of the averaged DFT value at the fundamental frequency to the amplitude of the averaged DFT value of the largest magnitude of harmonic or spurious signal component observed over the full Nyquist band.

**IEEE-1241:**

\[
\text{SFDR}_{dB} = 20 \log_{10} \left( \frac{|X_{avm}(f_i)|}{\max_{f_s \cap f_h} \{|X_{avm}(f_{sp})| \cup |X_{avm}(f_h)|\}} \right)
\]
The SFDR $dB$ give mathematically the same results.

**Signal-to-Noise and Distortion Ratio (SINAD):**

SINAD is the ratio of the signal to the total noise.

**IEEE-1241:**

\[
\text{SINAD} = \frac{\text{rms signal}}{\text{rms noise}}
\]

\[
\text{rms noise} = \frac{1}{M} \left[ \sum_{m=0}^{M-1} \left( E_{\text{avm}}(f_m) \right)^2 \right]^{1/2}
\]

DC, test frequencies $f_i$, $f_s - f_i$ excised

**DYNAD:**

\[
\text{SINAD}_{dB} = 10 \log \left( \frac{\sum_{k=1,k\neq J}^{M/2-1} |Y[k]|^2 + \frac{1}{2}|Y[J]|^2}{|NFI|^2} \right)
\]

\[
|NFI|^2 = \sum_{k=1,k\neq J,k\neq hJ}^{M/2-1} \frac{|Y[k]|^2 + \frac{1}{2}|Y[\frac{M}{2}]|^2}{\frac{M}{2} - h_{\text{max}}} \quad h = 2 \ldots h_{\text{max}}
\]

DC, test frequencies $f_i$, $(f_s - f_i)$ and $f_h[n]$ excised

- The IEEE standard calculates a ratio of the rms value of the fundamental to the rms noise, whereas DYNAD defines a more complicated ratio of the fundamental to the total noise. Noise floor is calculated, which is similar to the rms noise if also the harmonics are set to zero.

- IEEE defines SNHR instead of Noise floor.

- The rms noise is not subtracted from fundamental in the IEEE-1241 standard. This could causes big differences if the signal to noise ratio is small or the spectrum leaks.
• In frequency domain, DYNAD gives better results, but these expressions are difficult to adopt in time domain. Whereas, rms signal and rms noise, which are proposed by the IEEE-1241 std., can be easily calculated in time domain.

Note: Equation 6.5 can be incorrect on page 64 in the DYNAD. In the denominator, it seems to be necessary subtract the DC component. For example, if $h_{\text{max}} = 10$, the number of excised samples is 11 (9 harmonics + the fundamental + DC = 11) and not 10 ($h_{\text{max}} = 10$). We propose the next modification:

$$|NFL|^2 = \frac{\sum_{k=1, k \neq J, k \neq hJ}^{M/2-1} |Y[k]|^2 + \frac{1}{2} |Y[M/2]|^2}{M/2 - h_{\text{max}} - 1}$$

$h = 2 \ldots h_{\text{max}}$

Signal to Non-Harmonic Ratio (SNHR):

SNHR is the ratio of the signal to the portion of the noise that is not harmonic distortion.

<table>
<thead>
<tr>
<th>IEEE-1241:</th>
</tr>
</thead>
<tbody>
<tr>
<td>SNHR = \frac{\text{rms signal}}{\text{rms noise}}</td>
</tr>
<tr>
<td>\text{rms noise} = \frac{1}{M} \left[ \sum_{m=0}^{M-1} (N_{\text{avm}}(f_m))^2 \right]^{1/2}</td>
</tr>
<tr>
<td>DC, test frequencies $f_i$, $(f_s - f_i)$ and $f_h[n]$ excised</td>
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<table>
<thead>
<tr>
<th>DYNAD:</th>
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<tr>
<td>It is not considered.</td>
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• This rms noise is similar to the noise floor of DYNAD.
Effective Number of Bits (ENOB):

ENOB is a measure of the signal-to-noise and distortion ratio used to compare actual ADC performance to an ideal ADC.

\[
\text{IEEE-1241:} \\
\text{ENOB} = N - \log_2 \left( \frac{\text{rms noise}}{\text{ideal rms quantization error}} \right) \\
\text{ENOB} = \log_2 \left( \frac{\text{full scale range}}{\text{rms noise} \cdot \sqrt{12}} \right) \\
\text{ideal rms quantization error} = \frac{Q}{\sqrt{12}} \\
\text{ENOB} = \log_2 (\text{SINAD}) - \frac{1}{2} \log_2 (1.5) - \log_2 \left( \frac{A}{V/2} \right) \\
\text{SINAD} = (\sqrt{1.5}) \times \left( \frac{A}{V/2} \right) \times 2^{\text{ENOB}}
\]

It must be calculated after gain and offset corrections.

\[
\text{DYNAD:} \\
N_{\text{ef}} = \frac{\text{SINAD}_{\text{dBfs}} - 1.76}{6.02} \\
\text{SINAD}_{\text{dBfs}} = \text{SINAD}_{\text{dB}} - 20 \log(\text{SFSR}) \\
\text{SFSR} = \frac{\text{signal}}{\text{FullScale}}
\]

- In practice it is impossible to use a full scale sine wave to measure the dynamic parameters of an ADC, because of this, both standards propose corrections terms on the ENOB calculation.

Report of "ATE for FFT analysis of ADCs"
Results

General comments on the standards

The team has been reading these standards for a little time now, and has general comments.

Readability

In general the two standards are good in readability. One has to stay focused when reading, but this goes for all technical literature. The English language is good, with no observed typos or grammatical errors. The standards could easily be read by an engineer with the technical prerequisites.

Easiness of use

This topic has a lot of aspects. Easiness of use is something that has an unobiguous definition. In some aspects ease of use is lack of accuracy. These standards have their strong points and weak spots as all written documents. We still feel that the technical level of the standards do not exceed the level of an engineer that would need to program these measurements. They seem to be written from a perspective of being implemented in MATLAB.

Completeness

For completeness, the DYNAD standard did not cover the SNHR measurement, and thus this is a shortcoming from the viewpoint of this project. One point where there was a difference between the standards was in non-coherent sampling.

The DYNAD specifically expressed how the measurements should be carried out with which window that should be used for which desired accuracy of ADC, where the IEEE 1241 only mentioned that windowing should be applied. The standards do not leave any open points, and define everything in a complete manner, within the relevant chapters.

Effectiveness

Both of the standards cover how the measurements should be performed for the respective quantities. No iterative calculations are made in determining these quantities, which could influence the effectiveness.
A detailed list of references would be preferable, with references on where to read more about the definitions in the standards.

The developed ATE

The developed ATE is a virtual instrument (VI) that gives the measurements of a sinusoidal signal in both the IEEE-1241 and DYNAD standards. The user interface is displayed in Figure 1 and Figure 2. The VI below the user interface is designed as a hierarchical design, with each function defined as a sub-VI, creating a design that easily can be expanded with more functionality. This design method also minimizes redundancy in the VI, which contributes to a small and compact program.

In Figure 1, the amplitude of the input signal is near to the half of the full scale and the ADC is not saturated (leastwise it is not detectable in the time domain). The comparison of the considered parameters can be seen in the Output Parameters window.

In Figure 2, the ADC is saturated. It can be seen clipping results low.
frequency components in the frequency domain. This increase the harmonic distortion (THD) which decreases the SINAD, SFDR, and ENOB. SNHR does not be changed significantly because it contains the noise without harmonics and fundamental.

Conclusions and Future work

Conclusions

Reading and knowing the standards is essential when doing measurements on ADCs. The vision of these documents is that everyone should objectively compare parameters of ADCs without digging down into the specifications.

The implementation of the ATEs in LabView was not as easy as we initially thought, and we were thus not able to finish all the aspects of the tasks. Much focus has been spent into providing a starting point for future work in developing these ATEs all the way. Since the previous knowledge of
LabView usage was very little for four of five team members, the progress was halted. We still see that our understanding of the LabView environment has grown, and we are interested in using this tool more in our future work at our respective universities.

There were only minor errors in the DYNAD standard, which we have commented above. This is impressive in such a large document. We have also presented how to correct these errors.

Only small differences were observed between the two measurement methods. Some of the measures are explained in exactly the same way for both standards, but many of them have minor differences, as explained above. The DYNAD standard seems like a more profound measurement method, but at the cost of complexity. This is a natural consequence of the academic foundation in the DYNAD committee, compared to the more industrial aspect of IEEE-1241.

A standard defining these methods cannot and should not specify everything into the smallest detail, than the document should not be used. When something is written, the reader is left to interpret the message. One can easily see the conflicting interests. In the best of worlds, everyone should objectively present their work. Even if we cannot come here today, having a good standard is going to make things better. Here we all have a mission to spread the way to objectively measure an ADC.

**Future work**

The authors would like to extend this work to comprise even the non-coherent case, carefully described in DYNAD. This would require about a few more afternoons in work, and could easily be inserted into the structure of the program.

Moreover the authors would have liked to spend more time to make the VI more efficient from the execution time, and VI size. As the files are created in order to be distributed in order to spread the standards, the VIs should be small and fast.