20th IMEKO TC4 International Symposium and
18th International Workshop on ADC Modelling and Testing
Research on Electric and Electronic Measurement for the Economic Upturn
Benevento, Italy, September 15-17, 2014

# ADC Testing in Standardized and Non-standardized Ways, Using a Unified Framework

Tamás Virosztek, István Kollár

*Department of Measurement and Information Systems,*
*Budapest University of Technology and Economics,*
*H-1117 Budapest, Magyar tudósok körútja 2,*
virosztek@mit.bme.hu, kollar@mit.bme.hu

*Abstract* – **Several test methods are available to examine static and dynamic properties of analog-to-digital converters (ADCs). The most robust and straightforward ones are codified in international standards released by the IEEE, or by the IEC. These methods have been improved based on ideas proposed in scientific papers published in the field of ADC testing. However, there are algorithms and test techniques that are not yet standardized, but could be very useful to achieve more information concerning the device under test. These are predominantly amendments of the standard methods, elaborated to increase the accuracy, robustness, computation demand, etc. Nevertheless, it is important to be able to test ADCs strictly according to the standards, and it can also be important to use methods that go beyond the standardized ones in some aspects. This paper presents an idea to harmonize standard and non-standard ADC test methods in a single software tool on widely used platforms.**

## I. INTRODUCTION

This paper focuses on the extensions of standard ADC test methods performed via sinusoidal excitation. A technique is considered to be "standard", inasmuch it appears in the U.S. ([1] [2]) or European ([3], [4]) standards. The recorded sine wave can be used to estimate the static transfer characteristic of the device under test evaluating the histogram of the digital codes. The most important dynamic properties of the ADC: ENOB and SINAD can also be evaluated at the given frequency via sine wave fitting in the time domain. The idea is to develop a software environment that guides the user step by step from the raw sinusoidal measurement record to the estimated quality parameters of the device under test. In this path multiple options can be chosen or not, and several settings can be adjusted by the user. However, default options and settings are always provided, to ensure that a user without deeper knowledge in analog-to-digital conversion can also test the ADC by choosing the defaults offered by the program. Another very important aspect is to clearly indicate what is the standard way of processing the measurement record, and which are the

possible amendments of the standard methods. The default path of measurement evaluation leads to datasheet quantities achieved strictly following the standards.

## II. PREVIOUS EXPERIENCE

A user-friendly ADC test data evaluation program for MATLAB environment has been presented in 2013 [5]. This toolbox has already been downloaded from a dozen countries of the world, and feedback has arrived from users with different levels of domain knowledge, professional experience, etc. Most of the feedback mentioned the high amount of different options that can be confusing for users outside the field of ADC testing. Nevertheless it is desirable to make available the advanced methods that were published in scientific papers earlier. The idea to guide the user through the steps of signal processing, offering possible options and settings implies that the appropriate structure of a test data evaluation program is the "wizard" architecture. The following sections present the most important steps of ADC testing with sinusoidal excitation, from the aspect of standard and non-standard ways of measurement evaluation.

## III. CLASSIFICATION OF MEASUREMENT RECORDS

The appropriateness of the digital record shall be examined in different approaches.

### A. Overdrive

Saturation of the converter at the boundaries of the full scale affects almost all evaluation methods:

- In sine wave fit overdriven parts can be discarded. Thus fitting can be performed, and effective number of bits (ENOB) can be calculated sufficiently, however discarding samples decreases the amount of information available. Evaluating signal to noise and distortion ratio (SINAD) is more complicated. Distortion primarily shall represent the distortion caused by the the nonlinearity of the converter, instead of the distortion caused by saturation. Due to the unclear meaning of this quantity in

this case, the best choice is not to evaluate SINAD in presence of overdrive.

- In histogram test overdriving the ADC under test is pronouncedly recommended to cover the full scale range. Nevertheless too intensive overdrive decreases the number of samples in the intermediate digital codes, thus decreases the accuracy of transition level estimators. Appropriate level of overdrive can be calculated using the formulas described in [6]. Using simple initial estimators for amplitude and DC level of the sine wave, the program informs the user whether the amount of overdrive makes the record suitable for histogram testing or not.

- In FFT test, overdrive makes very difficult to evaluate the spurious-free dynamic range (SFDR) properly. The harmonic components appearing due to the saturation mislead the estimated of SFDR. In case of overdriven measurement record, user can decide not to evaluate SFDR or to apply corrections on the measurement record [7] before performing FFT test.

### B. Coherence and number of samples

Coherent sampling is indispensable to perform histogram test appropriately. This condition is easy to prescribe, but more complex to investigate properly. To qualify the measurement record concerning coherence, it is necessary to have a sufficiently accurate frequency estimator to examine the phase distribution of the recorded samples. This way the measure of incoherence can be expressed using e.g. the ratio of the samples in fractional periods and the total number of samples. [8] proposes an effective algorithm to examine coherence properly with acceptable computation efforts. This method is integrated into this software tool.

Uncertainty of the estimators of the transition levels also depends on the number of samples. The required record length can be calculated using the resolution of the ADC, the deviation of noise, the amount of overdrive, and the specified accuracy and confidence level [6]. To decide whether the record is appropriate for histogram testing or not, the record shall be examined with user-specified accuracy of transition levels and user-specified confidence level.

### C. Results of classification

The program decides whether the measurement record is appropriate for a certain test method or not. The methods available are the followings:

- Sine wave fit in least squares (LS) sense
- Histogram test
- FFT test
- Sine wave fit in maximum likelihood (ML) sense

A record can be classified with respect to each method as "appropriate", "inappropriate", or "appropriate with restrictions". A measurement record is considered "appropriate" if no doubt arises concerning the result of evaluation: on the one hand, the algorithms will certainly converge to a reasonable result, on the other hand, these results are accurate enough to rely on them when evaluating a converter. E. g., for histogram testing, it is not enough to use a coherently sampled and slightly overdriven signal which ensures reasonable and likely results for transition level estimators. The average number of samples per code bin shall also be considered very carefully as this quantity mostly determines the accuracy and the confidence level of transition level estimators (as mentioned in section III. B. and described in [6]). Thus when "appropriateness" of a record shall be determined, an accuracy criterion and a confidence level is required from the user. However, reaching grade "appropriate" is very difficult for an ordinary measurement record. It indicates that the user can trust blindly in the results of evaluation, without any doubt. The most likely outcome of classification is "with restrictions". In this case possible problems regarding the measurement record are highlighted, and user is warned for the possibly of misleading evaluation results. Grade "inappropriate" is also unlikely. This result can be achieved in cases when the data vector is entirely unsuitable to perform a certain test method, e.g. for sine wave fitting the record does not contain at least five integer cycles of the sine wave (see section 5.3 in [1]).
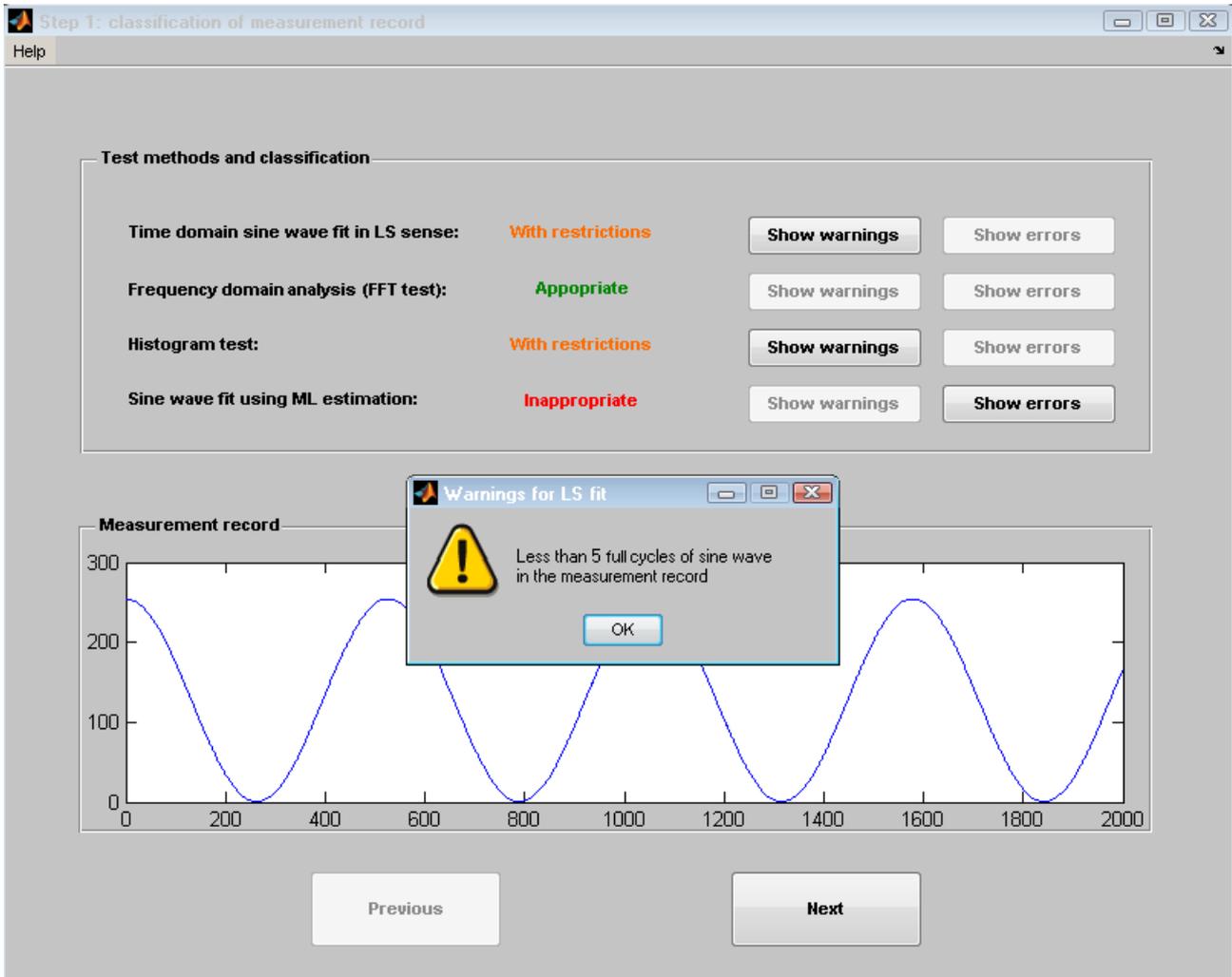
*Fig. 1. Classification of measurement record.*

## IV. PROCESSING MEASUREMENT DATA

The test methods used in this software mentioned in earlier are described in detail in papers [1], [2], [3] and [9]. In the followings some questions are investigated concerning which are the standard ways to perform these test methods, and which are the amendments that guarantee better performance, but are besides the standards. ML fit is an entirely non-standard way to test ADCs, however the user's choice regarding the followings can also be important in ML fit, thus aspects of ML fit are also mentioned below.

### A. Initial frequency estimator

In iterative optimizing processes like the 4-parameter sine wave fit in least squares (LS) sense, or the maximum likelihood (ML) estimation of signal and ADC parameters, the initial estimator of the sine wave frequency is a key issue regarding the convergence of the algorithm. This initial estimator can be achieved in several ways:

- nominal frequency of the generated sine wave

- maximum of the periodogram of the record
- interpolating the FFT of the record
- fitting polynomials (e.g. a parabola) to the periodogram of the record
- windowing in time domain and fitting the windowed data in frequency domain [10]

The estimation is more and more accurate in the list of methods, and the computation demand increases as well. The user can select a technique to use, the default is the one recommended by the standards. Four parameter fit is described most detailed in [1] and [2], thus default initial frequency estimator is achieved as the IEEE standards prescribe to do so. Due to the results published in [11] and [12], IEEE and IEC standards largely harmonize, especially regarding formulas and signal processing methods. Inasmuch different algorithms (or different settings) are recommended by the IEEE and the IEC standards to calculate a quantity, the user has to choose which standardized method to use.

### B. Numerical recipes to optimize

Test methods like histogram test and FFT test require the application of closed-form expressions, thus can be performed in a single step. The simplest, 3-parameter sine wave fit in LS sense can also be performed without iterations. However 4-parameter LS fit or ML estimation of sine wave parameters can only be solved using iterative algorithms. In this subsection numerical recipes to optimize the 4-parameter LS and the 5-parameter ML cost function are discussed.

For an LS fit, Annex B of [1] describes the proposed iterative algorithm to estimate frequency, amplitude, phase and DC level simultaneously. This is the Gauss-Newton method applied to the least squares cost function with 4 free parameters. However the 4-parameter LS cost function can also be optimised otherwise. The standard solver for nonlinear LS problems in MATLAB Optimization toolbox, *lsqnonlin* [13] provides a very robust algorithm to optimize nonlinear LS cost functions. This method uses finite differences to approximate the partial derivatives and to build the Jacobian. Optimization steps can be either trust region reflective, or can be forced to be Levenberg-Marquardt (the latter will be detailed further regarding the optimization for ML fit). Using *lsqnonlin* ensures better performance than the Gauss-Newton method does (e. g. in case of uncertain initial frequency estimator). It is recommended to use *lsqnonlin* when standard Gauss-Newton iteration diverges or gives unlikely results. As the LS fit is nonlinear only in the frequency parameter, another simple algorithm can be used to estimate sine wave parameters. The frequency axis can be scanned starting from the initial frequency estimator, performing a linear 3-parameter LS fit at each iteration. In this way, the LS cost function can be examined as a function of the frequency in a certain region. This method is recommended for debug purposes in the (unlikely) cases when the numerical methods mentioned above fail to converge to a reasonable result.
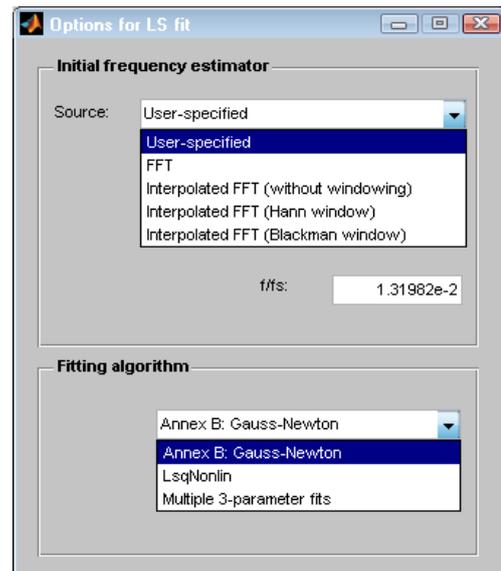


Fig. 2. Options for LS fit.

In ML estimation, the signal parameters are achieved via numerical optimization of the negative log-likelihood function of the observations. This task can be solved in multiple ways:

- Gradient-based deterministic algorithms: the first-order gradient descent method, or the Levenberg-Marquardt method which requires calculation of the second order partial derivatives.
- Stochastic algorithms like differential evolution (DE) [14] which uses the function values only, not the derivatives, thus does not require the objective function to be differentiable or even continuous.

Certainly, other optimization techniques can also be used, but the ones mentioned above are appropriate to solve the ML problem. In the MATLAB toolbox published as [15], the gradient-based Levenberg-Marquardt method has been implemented. This algorithm has multiple parameters to be set, most of them are concerned for the termination of the iteration (these are detailed in IV. C.). The parameter $\lambda$ determines the direction of the step: high $\lambda$ ensures smaller, nearly steepest-descent steps, low $\lambda$ allows larger, nearly Gauss-Newton steps which target the extremum of a paraboloid. Thus the initial value of $\lambda$ determines the path of the optimization. Initial $\lambda$ is calculated by the software using the eigenvalues of the initial Hessian matrix, however, the user can also specify alternative initial $\lambda$ values to modify the trajectory of iterations in the parameter space. Alternative initial $\lambda$s can also be specified, related to the maximal eigenvalue of the initial Hessian matrix.

### C. Termination criteria

As ML estimation does not yet appear in the

standards for ADC testing, neither the numerical method, nor the termination criteria are specified. As the user can select the algorithm to optimize, he can choose the conditions to terminate the iteration also. The most frequently used criteria are the followings:

- maximum number of iterations
- maximum number of objective function evaluations
- termination tolerance on the value of the objective function
- termination tolerance on the alteration of the parameter vector (e.g. on $\|p_k - p_{k-1}\|_2$)

User can define these values, or can rely on the default settings offered by the program.
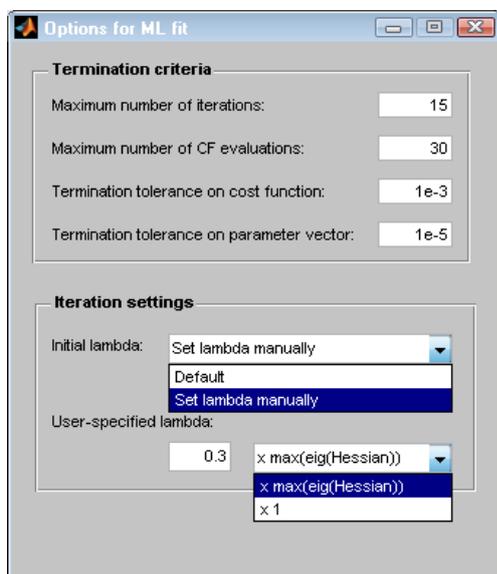
*Fig.3. Options for ML fit.*

## V. DOCUMENTING THE RESULTS OF MEASUREMENT EVALUATION

In the presentation of ADC test results the measurement and the evaluation shall be separated clearly. The measurement descriptor contains the raw data and the circumstances of the measurement. A measurement descriptor can be processed in multiple ways, using several different settings, thus evaluation results can be different, depending on the method and the settings applied.

The evaluation results are collected in a structured format: an XML file. This document contains the description of measurement, the evaluation methods and settings, and the evaluation results. As a record can be processed different ways, multiple evaluation result documents can belong to a single measurement descriptor.
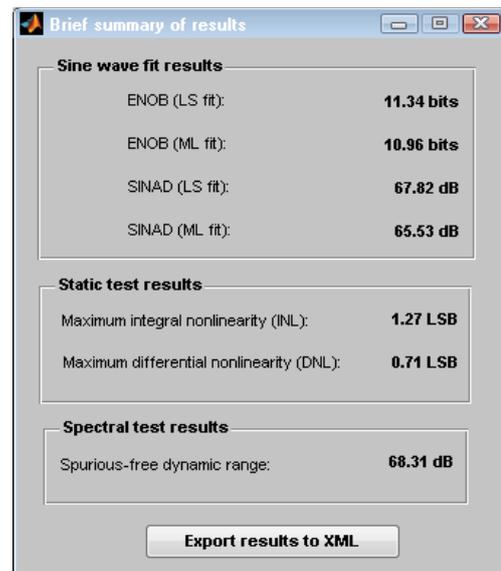
*Fig. 4. Brief summary of results*

## VI. CONCLUSIONS

Using the software tool introduced above standard and non-standard ADC test methods can be unified and used in a common framework. Users can test ADCs strictly according to the standards using default options and settings, and can perform advanced measurement evaluation using the non-standard methods (or extensions of the standard methods) to achieve more accurate results.

Both of these tasks can be solved without any programming owing to the graphical user interface. The approach of the program is functional: it focuses on the task to be solved, the user can explore the details as much as he wants. Thus this software is also suitable for engineers without deeper knowledge in the field of ADC testing.

This software tool is to be presented in the Software Session of the 20th IMEKO TC-4 International Symposium [16].

## REFERENCES

[1] IEEE Std. 1241-2010: "IEEE Standard for Terminology and Test Methods for Analog-to-Digital Converters"; DOI: 10.1109/IEEESTD.2011.5692956, http://ieeexplore.ieee.org/xpl/mostRecentIssue.jsp?punumber=5692954

[2] IEEE Std. 1057-2007: "IEEE Standard for Digitizing Waveform Recorders"; DOI: 10.1109/IEEESTD.2008.4494996, http://ieeexplore.ieee.org/xpl/mostRecentIssue.jsp?punumber=4494800

[3] IEC Std. 60748-4: "Semiconductor devices - Integrated circuits - Part 4: Interface integrated circuits", Ed. 2.0b, 1997,

http://webstore.iec.ch/preview/info_iec60748-4.%7Bed2.0%7Db.pdf

[4] IEC Std. 60748-4-3 "Semiconductor devices – Integrated circuits – Interface integrated circuits – Dynamic criteria for analogue-digital converters", Ed. 1.0, 2006, http://webstore.iec.ch/preview/info_iec60748-4-3%7Bed1.0%7Den.pdf

[5] Tamás Virosztek, István Kollár: "User-friendly Matlab tool for easy ADC testing" 19th IMEKO TC4 Symposium and 17th IWADC Workshop: Advances in Instrumentation and Sensors Interoperability. Barcelona, Spain, 18-19th July, 2013, Paper 113., http://mycite.omikk.bme.hu/doc/144251.pdf

[6] Jerome Blair: "Histogram Measurement of ADC Nonlinearities Using Sine Waves", IEEE Transactions on Instrumentation and Measurement, vol. 43, no. 3, June 1994. pp. 373-383. http://ieeexplore.ieee.org/stamp/stamp.jsp?arnumber=00293454

[7] Li Xu, Siva Kumar Sudani and Degang Chen: "Efficient Spectral Testing With Clipped and Noncoherently Sampled Data" IEEE TRANSACTIONS ON INSTRUMENTATION AND MEASUREMENT, 2014 http://ieeexplore.ieee.org/stamp/stamp.jsp?arnumber=06687238

[8] Vilmos Pálfi, István Kollár: "Improving the result of the histogram test using a fast sine fit algorithm." 19th IMEKO TC 4 Symposium and 17th IWADC Workshop: Advances in Instrumentation and Sensors Interoperability. Barcelona, Spain, 18-19th July, 2013, Paper 118., http://mycite.omikk.bme.hu/doc/144253.pdf

[9] Ján Šaliga, Linus Michaeli, Ján Buša, Jozef Lipták, István Kollár, Tamás Virosztek: "A Comparison of Least Squares and Maximum Likelihood Based Sine Fittings in ADC Testing." MEASUREMENT (ISSN: 0263-2241) 46: pp. 4362-4368. (2013) DOI: 10.1016/j.measurement.2013.05.004, http://mycite.omikk.bme.hu/doc/142952.pdf

[10] Pálfi V, Kollár I: "Acceleration of ADC test with sine wave fit" IEEE TRANSACTIONS ON INSTRUMENTATION AND MEASUREMENT 62:(5) pp. 880-888. Paper 2243500. (2013)., DOI: 10.1109/TIM.2013.224350, http://mycite.omikk.bme.hu/doc/137087.pdf

[11] E. Balestrieri, P. Daponte, S. Rapuano: "ADC Standard Harmonization: Comparison of Test Methods." I2MTC 2008 – IEEE International Instrumentation and Measurement Technology Conference, Victoria, Vancouver Island, Canada, 12-15 May, 2008. DOI: 10.1109/IMTC.2008.454725, http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=4547205

[12] E. Balestrieri, P. Daponte, S. Rapuano: "Harmonization of Standard Procedures for ADC Time Domain Dynamic Testing" I2MTC 2009 – IEEE International Instrumentation and Measurement Technology Conference, Singapore, 5-7 May 2009., DOI: 10.1109/IMTC.2009.5168644 , http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=5168644

[13] Solve nonlinear least-squares (nonlinear data fitting) problems. http://www.mathworks.com/help/optim/ug/lsqnonlin.html

[14] Differential Evolution Homepage: http://www1.icsi.berkeley.edu/~storn/code.html

[15] Virosztek, T., Pálfi V., Renczes B., Kollár I., Balogh L., Márkus J., ADCTest project site: http://www.mit.bme.hu/projects/adctest/ 2000-2014

[16] Virosztek T., I. Kollár, ADCTest Toolbox for MATLAB. 20th IMEKO TC-4 International Symposium on Measurement of Electrical Quantities and 18th TC-4 Workshop on ADC and DAC Modelling and Testing Benevento, Italy, Sep 15-17, 2014. Paper in the SW session.