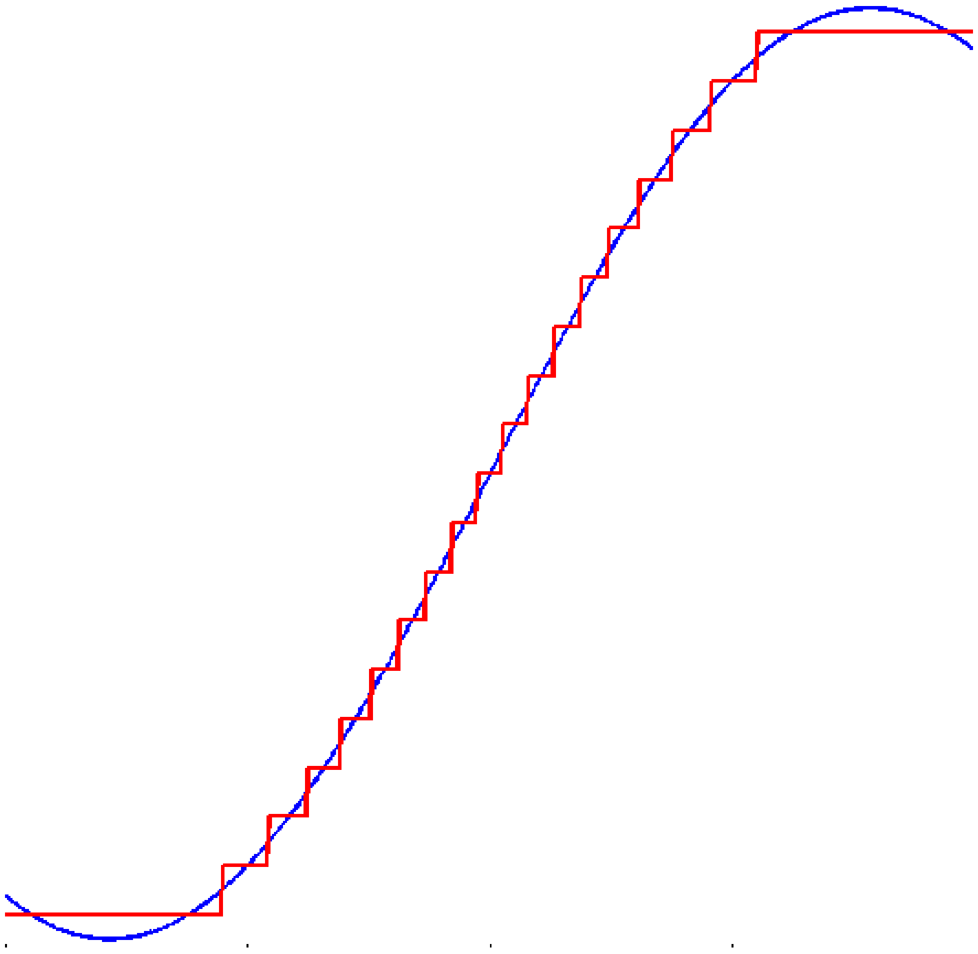
ADC test data evaluation program for MATLAB

User's manual



Version 4.3

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1 Introduction

1.1 Scope

This software is a MATLAB toolbox with graphical user interface: a collection of functions which can be executed in MATLAB environment. This toolbox provides the implementation of the following algorithms used in ADC testing:

- Four parameter sine wave fitting method described in standard IEEE-1241
- Maximum likelihood estimation of signal and ADC parameters (with sinusoidal excitation signal)
- Histogram test using sinusoidal excitation signal
- FFT test

Furthermore the toolbox contains a simple tool to generate simulated measurement data: this possibility is useful to test and compare the fitting algorithms.

1.2 What's new?

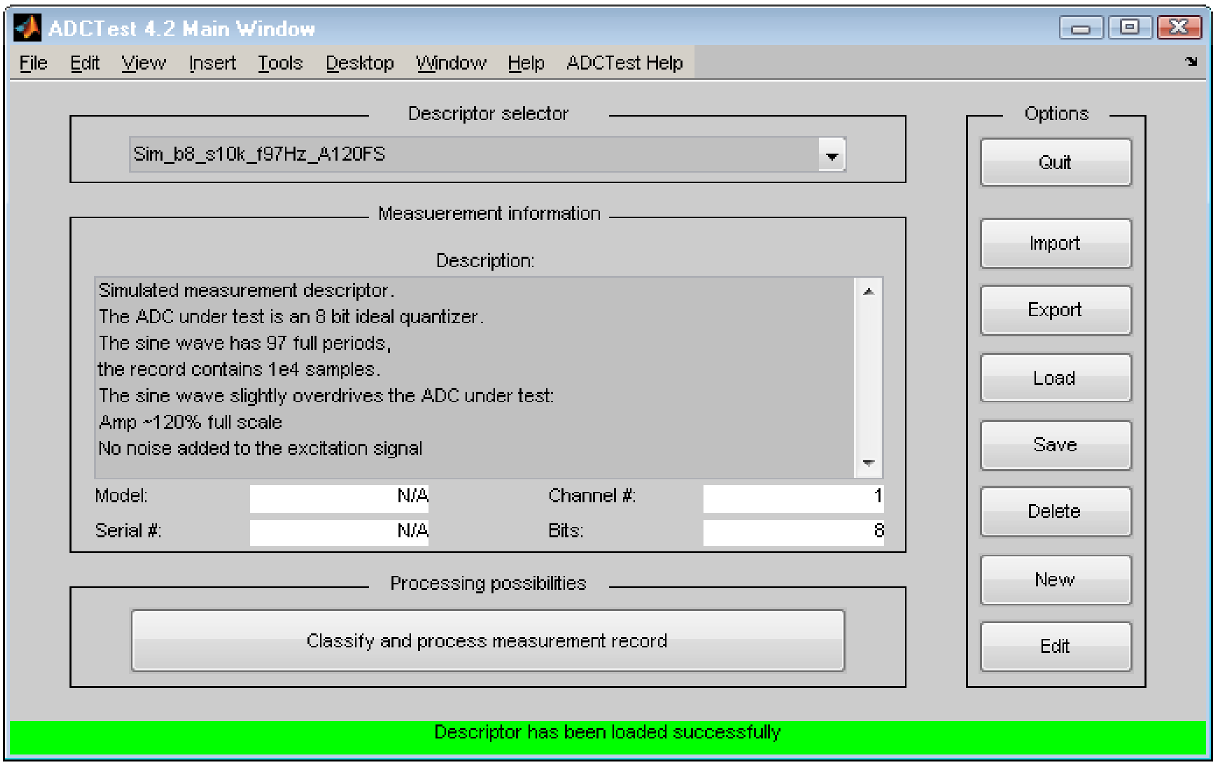
Compared to the previous versions of ADCTest (ver 3.1 3.2 3.3) the most important new feature is the implementation of maximum likelihood (ML) parameter estimation to sinusoidal excitation signal [2]. The estimation of the converter's static transfer characteristic via histogram test is also a new possibility in this toolbox. This method is based on [3]. The software has been expanded with FFT test function. The simulated measurement generator tool is a side-effect of the developement process.

2 Installation

1. Download the latest version of adctest toolbox from the project site ([5]) in a zip file.
2. Extract the zip file to a folder used to store MATLAB toolboxes e. g. C:\Program Files\MATLAB\toolbox
3. Start MATLAB.
4. Add the directory (where you have installed the toolbox) to MATLAB search path using the *File->Set Path* menu or the *addpath* command.
5. Type *adctest* to the MATLAB command line to launch the GUI.

3 Getting started

Once the toolbox is launched, the main window appears (figure 1).



Sim_b8_s10k_f97Hz_A120FS

Description:

Simulated measurement descriptor.
The ADC under test is an 8 bit ideal quantizer.
The sine wave has 97 full periods,
the record contains 1e4 samples.
The sine wave slightly overdrives the ADC under test:
Amp ~120% full scale
No noise added to the excitation signal

Model: N/A
Channel #: 1
Serial #: N/A
Bits: 8

Descriptor has been loaded successfully

Figure 1: Main window of the toolbox

On the right side of the window the following data handling options are available:

- Importing multiple measurement descriptors from wokspace
- Exporting multiple measurement descriptors to workspace
- Loading a single measurement descriptor
- Saving the current measurement descriptor
- Deleting the current measurement descriptor
- Creating a new measurement descriptor
- Editing an exising measurement descriptor

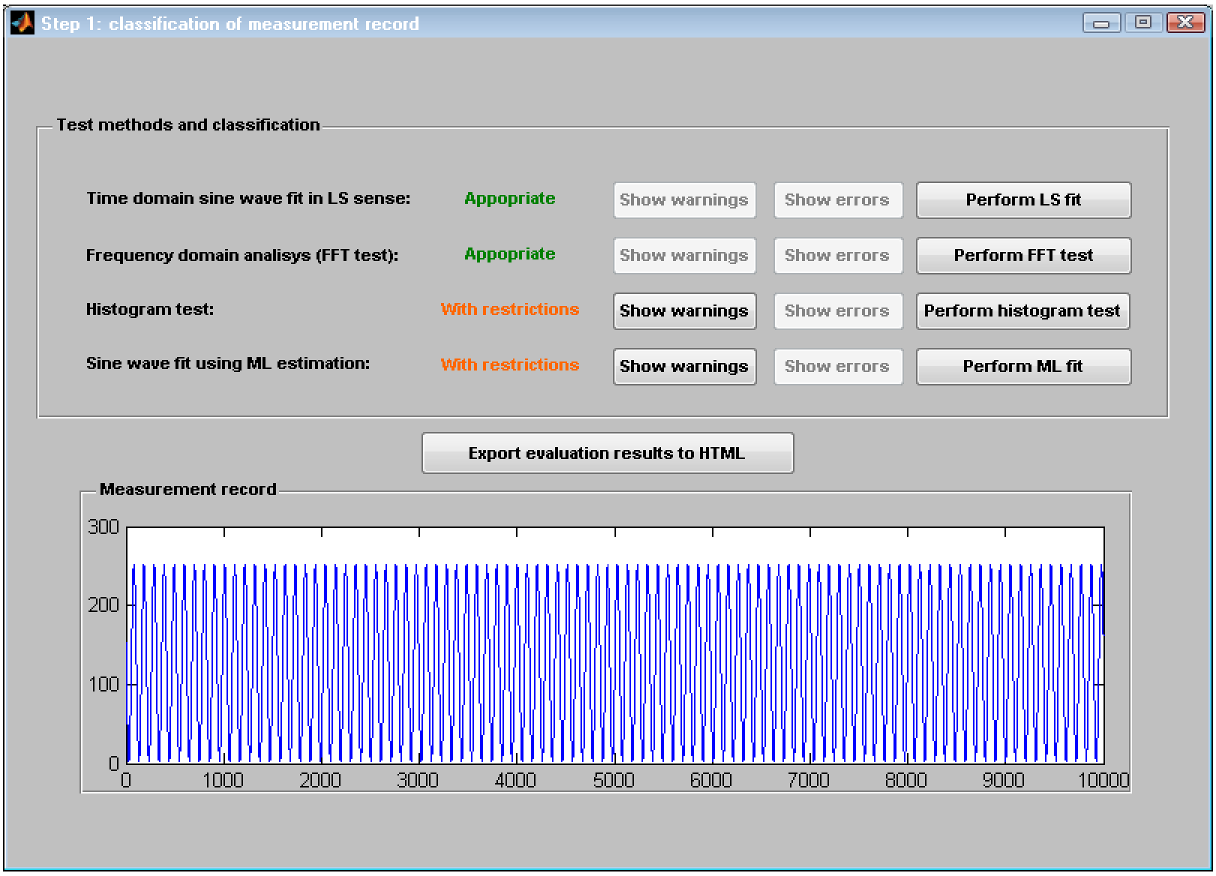
At the bottom of the window the „Classify and process measurement record” pusbutton appears. Using this pushbutton user can reach the classification dialog box. This window shows the classification results with respect to the following test methods:

- Four parameter sine wave fit in LS sense
- Maximum likelihood estimation of signal and ADC parameters
- Histogram test of the ADC using sinusoidal excitation signal
- FFT test of the ADC

The result of classification can be

- Appropriate
- Appropriate with restrictions
- Inappropriate

Classification window appears in figure 2



Step 1: classification of measurement record

Test methods and classification

Time domain sine wave fit in LS sense: Appropriate

Frequency domain analisys (FFT test): Appropriate

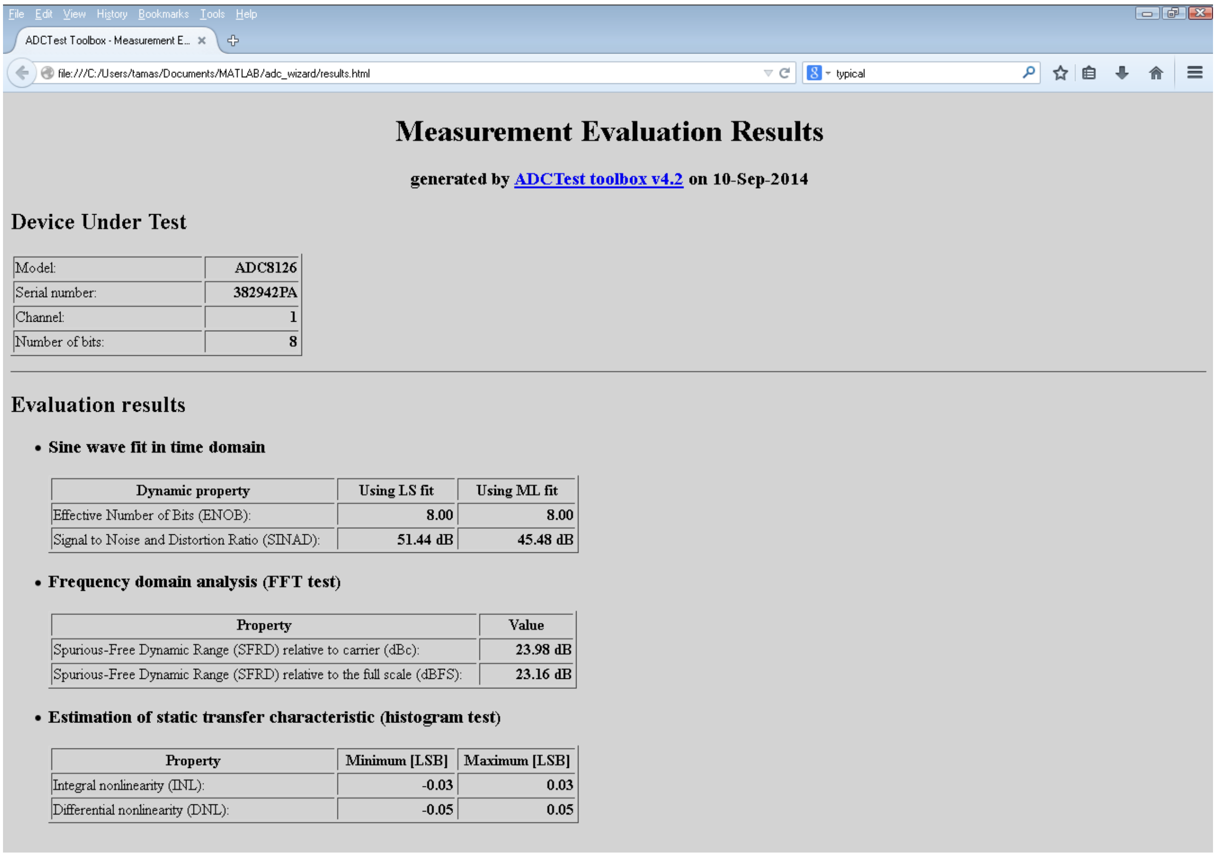
Histogram test: With restrictions

Sine wave fit using ML estimation: With restrictions

Measurement record

Figure 2: Classification of measurement record

If a measurement record is „Appropriate” or „Appropriate with restrictions” to process in a certain way, the data can be evaluated using the active pushbuttons („Perform ...”)on the right side. Possible warnings can be displayed using the „Show warnings” pushbutton. If the measurement record is inappropriate to process, an error message can be read using the „Show errors” pushbutton. The evaluation results can be exported to a HTML document using the „Export results to HTML” pushbutton. A typical HTML report appears in figure 3


File Edit View History Bookmarks Tools Help
ADCTest Toolbox - Measurement E...
file:///C:/Users/tamas/Documents/MATLAB/adc_wizard/results.html
typical

Measurement Evaluation Results

generated by ADCTest toolbox v4.2 on 10-Sep-2014

Device Under Test

Model:	ADC8126
Serial number:	382942PA
Channel:	1
Number of bits:	8

Evaluation results

- **Sine wave fit in time domain**

Dynamic property	Using LS fit	Using ML fit
Effective Number of Bits (ENOB):	8.00	8.00
Signal to Noise and Distortion Ratio (SINAD):	51.44 dB	45.48 dB

- **Frequency domain analysis (FFT test)**

Property	Value
Spurious-Free Dynamic Range (SFRD) relative to carrier (dBc):	23.98 dB
Spurious-Free Dynamic Range (SFRD) relative to the full scale (dBFS):	23.16 dB

- **Estimation of static transfer characteristic (histogram test)**

Property	Minimum [LSB]	Maximum [LSB]
Integral nonlinearity (INL):	-0.03	0.03
Differential nonlinearity (DNL):	-0.05	0.05

Figure 3: Evaluation results exported to a HTML report

4 Description of measurements

The description of measurements is realized using XML files since version 3.3. The proper schema definition of these XML files is available on the project's web site ([5]). These descriptors have mandatory and optional fields. The descriptors must contain

- The name of the measurement: a short but informative title. Usually used to be the filename of the XML
- The model of the ADC under test
- The serial number of the ADC under test
- The resolution (bit number) of the ADC under test
- The measurement data: the record of the ADC's output (in digital codes).

The descriptor also may contain the following information:

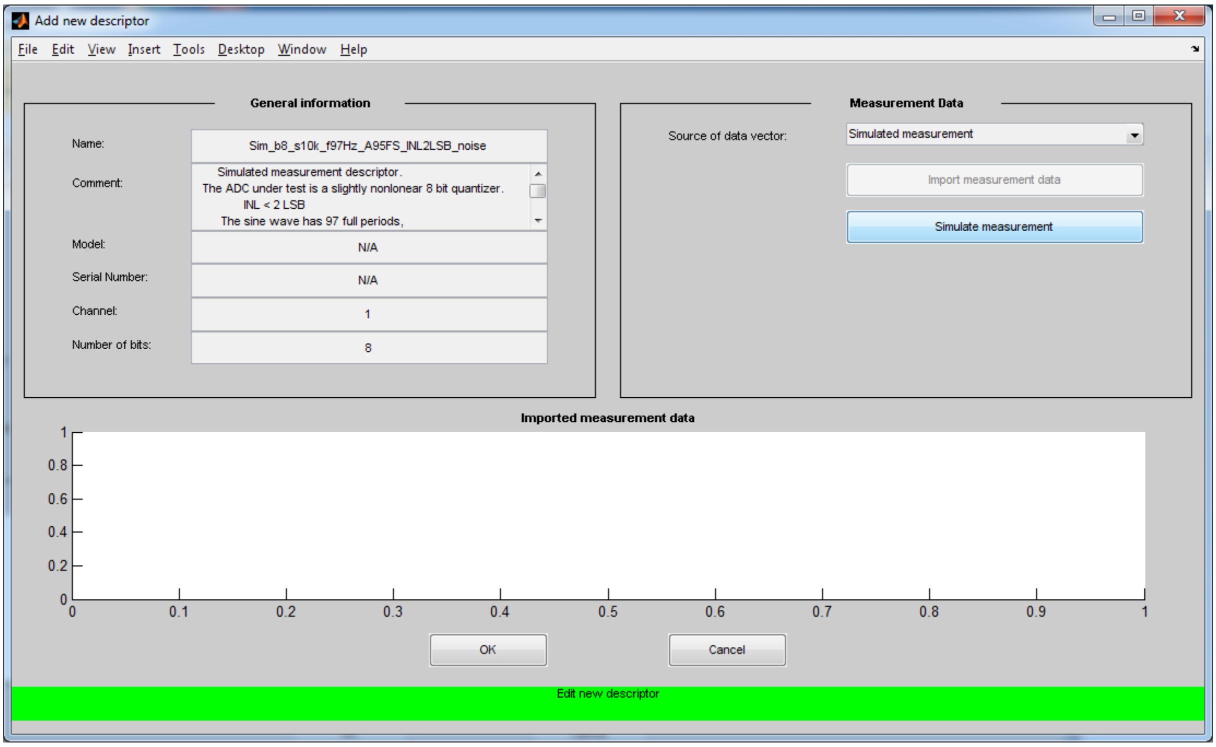
- Comment: a more detailed description of measurement
- Channel: useful if the ADC under test is a multi-channel device
- Parameters: a feature to support test runs. In case of simulated measurement the original signal parameters and the ADC's static transfer characteristic (INL vector) can be saved. Thus accuracy of parameter estimation can be calculated using the original and the fitted values.

4.1 Loading an existing measurement descriptor

This function is available from main window, using the Load pushbutton. If the XML file is deficient, the load function returns error messages or warnings: errors, when the missing fielss are mandatory, and warnings if the missing fields are optional.

4.2 Creating a new measurement descriptor

This function is available from the main window, using the New pushutton. A dialog box appears (figure 4), where all properties of the measurement descriptor can be set.



Add new descriptor

General information

Name: Sim_b8_s10k_f97Hz_A95FS_INL2LSB_noise

Comment:
Simulated measurement descriptor.
The ADC under test is a slightly nonlonear 8 bit quantizer.
INL < 2 LSB
The sine wave has 97 full periods,

Model: N/A

Serial Number: N/A

Channel: 1

Number of bits: 8

Measurement Data

Source of data vector: Simulated measurement

Edit new descriptor

Figure 4: Add new descriptor dialog box

In case of real measurement the ADC output data vector can be loaded from MATLAB workspace. In case of simulated measurement a simulation tool can be started (see 4.7).

4.3 Editing an existing measurement descriptor

This function is available from main window, using the Edit pushbutton. The dialog box is similar to the dialog box "Add new descriptor" , but the original properties and values of the descriptor are displayed in the appropriate fields of the window.

4.4 Batch import of measurement descriptors

This function is available from main window, using the Import pushbutton. A variable from MATLAB workspace, that contains multiple descriptors can be imported to the toolbox. Note that no software component checks that your variable is appropriate: if the format of the data in this variable is not matchingh, strange errors can occur. Used to perform test runs.

4.5 Batch export of measurement descriptors

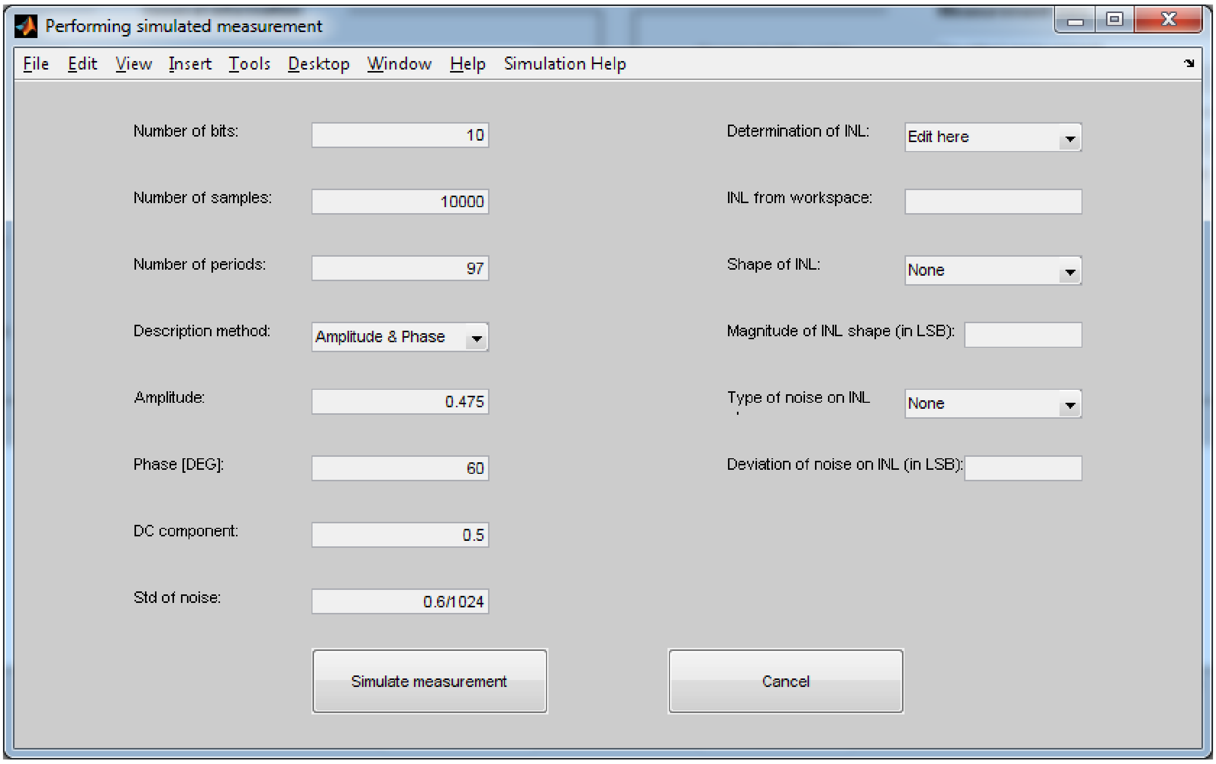
This function is available from main window, using the Export pushbutton. All the measurement descriptors that are currently in the memory, will be copied to the workspace. The variable specified by the user is a cell array, each cell contains one measurement.

4.6 Saving a measurement descriptor

This function is available from main window, using the Save pushbutton. The filename suggested by the save dialog box is the name of the descriptor. Keeping this file naming convention is recommended.

4.7 Creating a new simulated measurement descriptor

This function is available from dialog box "Add new descriptor". If the "Source of the data vector" is changed from "Real measurement" to "Simulated measurement", a pushbutton "Simulate Measurement" appears. This button launches the simulation tool (figure 5).



Number of bits: 10

Number of samples: 10000

Number of periods: 97

Description method: Amplitude & Phase

Amplitude: 0.475

Phase [DEG]: 60

DC component: 0.5

Std of noise: 0.6/1024

Determination of INL: Edit here

INL from workspace:

Shape of INL: None

Magnitude of INL shape (in LSB):

Type of noise on INL: None

Deviation of noise on INL (in LSB):

Figure 5: Simulate measurement dialog box

In this dialog box both the excitation signal parameters and the ADC parameters can be set. The sine wave can be described in two ways: amplitude and initial phase, or cosine and sine coefficient. The nonlinearity can be imported from workspace (e.g. the nonlinearity of a previously measured ADC), or can be assembled in this dialog box. The nonlinearity assembler uses two components: a component that determines the nature of the nonlinearity (e. g. a rasied cosine (Hann) window), and a component that adds some noise to the INL vector. This way the values of transition levels will not be so regular: the transfer characteristic will be more lifelike. Not that the "Deviation of noise on INL" means the standard deviation of noise in both cases: so in the case of normally distributed noise, as in the case of uniformly dirstibuted noise.

5 Evaluation of measurements

5.1 Histogram test

Histogram test is the estimation of the static transfer characteristic of the ADC under test. The test uses the histogram of measured data and calculates the INL estimators described in [4]. A formula about the accuracy of these estimators is given in [3].

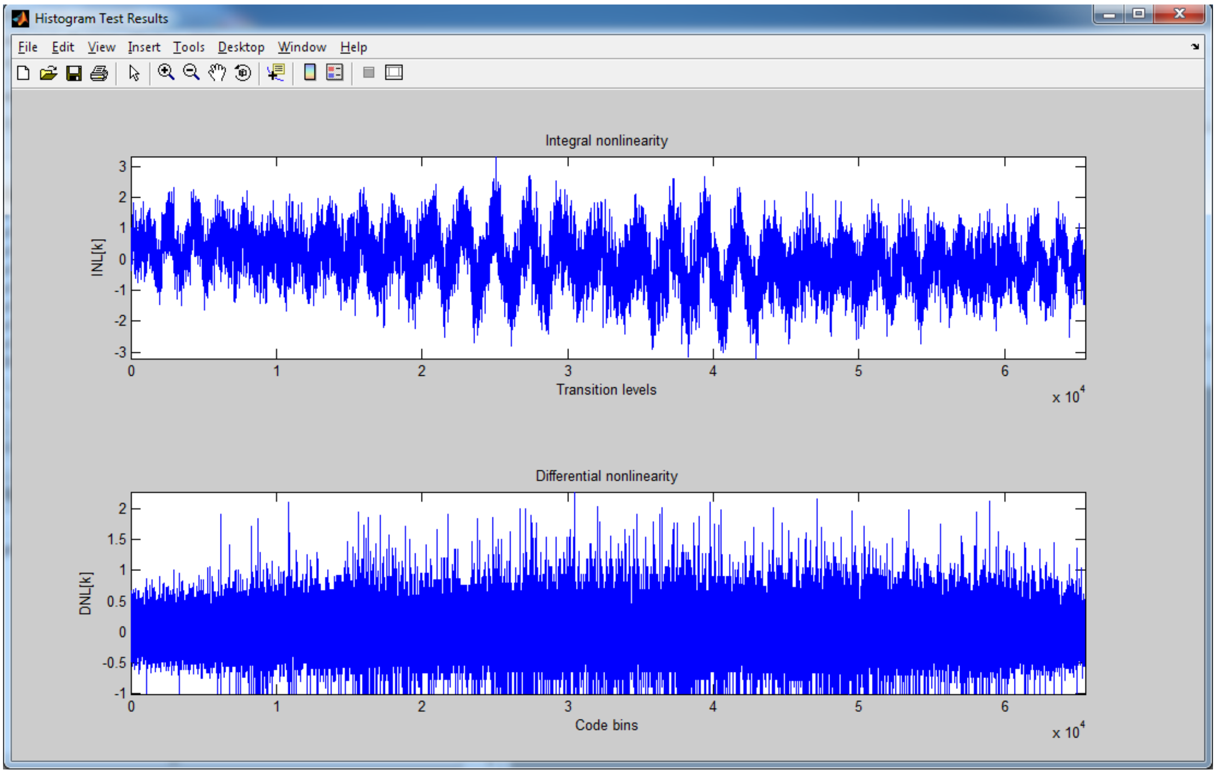
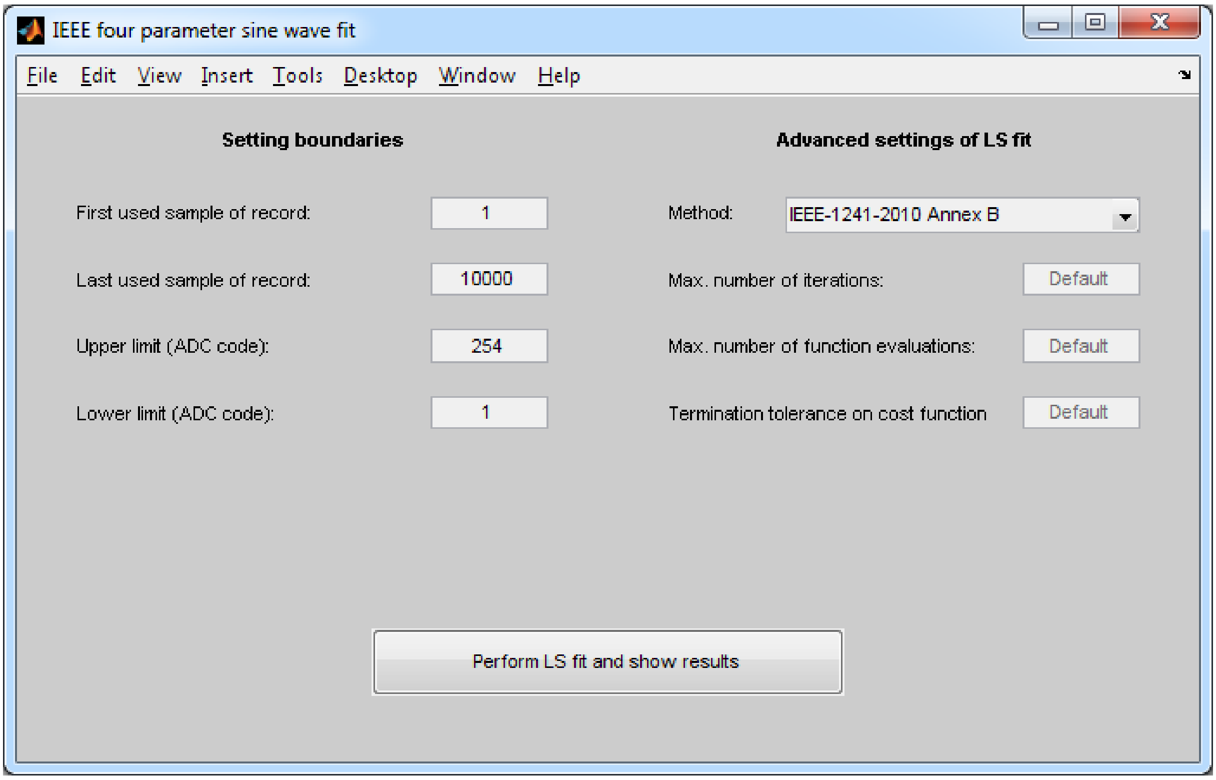


Figure 6: Result window of histogram testing

5.2 Four parameters sine wave fitting test

To perform four parameter sine wave fit according to standard IEEE-1241-2010, some parameters of optimization must be set. Before starting the optimization, a dialog box appears (figure 7).


IEEE four parameter sine wave fit
File Edit View Insert Tools Desktop Window Help

Setting boundaries

First used sample of record: 1

Last used sample of record: 10000

Upper limit (ADC code): 254

Lower limit (ADC code): 1

Advanced settings of LS fit

Method: IEEE-1241-2010 Annex B

Max. number of iterations: Default

Max. number of function evaluations: Default

Termination tolerance on cost function Default

Perform LS fit and show results

Figure 7: Settings window for 4 parameter LS fit

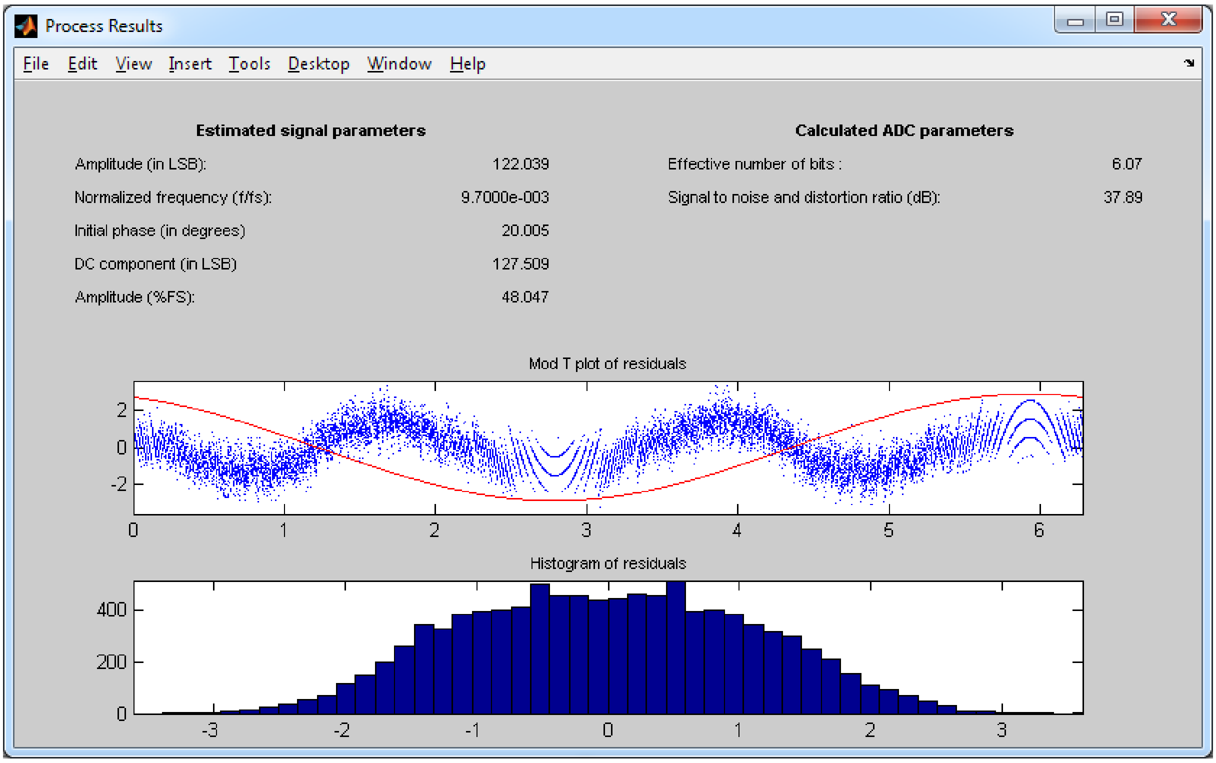
On the left side, the boundaries of the record can be set. Using "First sample of record" and "Last sample of record" the useless parts of recording (like initial transients) can be cut. "Upper boundary" and "Lower boundary" determines the code range, where the samples are taken into consider. This function is used to throw samples where the ADC is overdriven. Not that the default lower boundary is the lowest code of ADC + 1, the default upper boundary is the highest code of ADC - 1.
On the right side the parameters of optimization can be set. The following fitting methods are available:

- IEEE-1241-2010 Annex B: performs the method described in [1]
- LsqNonlin: calls the built-in nonlinear least squares solver function of MATLAB Optimization toolbox. This method is more time-consuming, but can be more robust in some cases.

In case of LsqNonlin, three other parameters of optimization can be set:

- Maximal number of iterations
- Maximal number of cost function evaluations
- Termination tolerance on cost function

The results of the sine wave fitting appear in the results window (figure 8).



Estimated signal parameters

Amplitude (in LSB): 122.039

Normalized frequency (f/fs): 9.7000e-003

Initial phase (in degrees) 20.005

DC component (in LSB) 127.509

Amplitude (%FS): 48.047

Calculated ADC parameters

Effective number of bits : 6.07

Signal to noise and distortion ratio (dB): 37.89

Figure 8: Results window for 4 parameter LS fit

This dialog box displays the estimated sine wave parameters (amplitude, frequency, initial phase, DC component), and the ADC parameters: effective number of bits (ENOB), and signal to noise and distortion ratio (SINAD). ADC parameters calculated from the difference between the fitted sine wave and the measurement data, the residuals. The residuals are displayed in two ways:

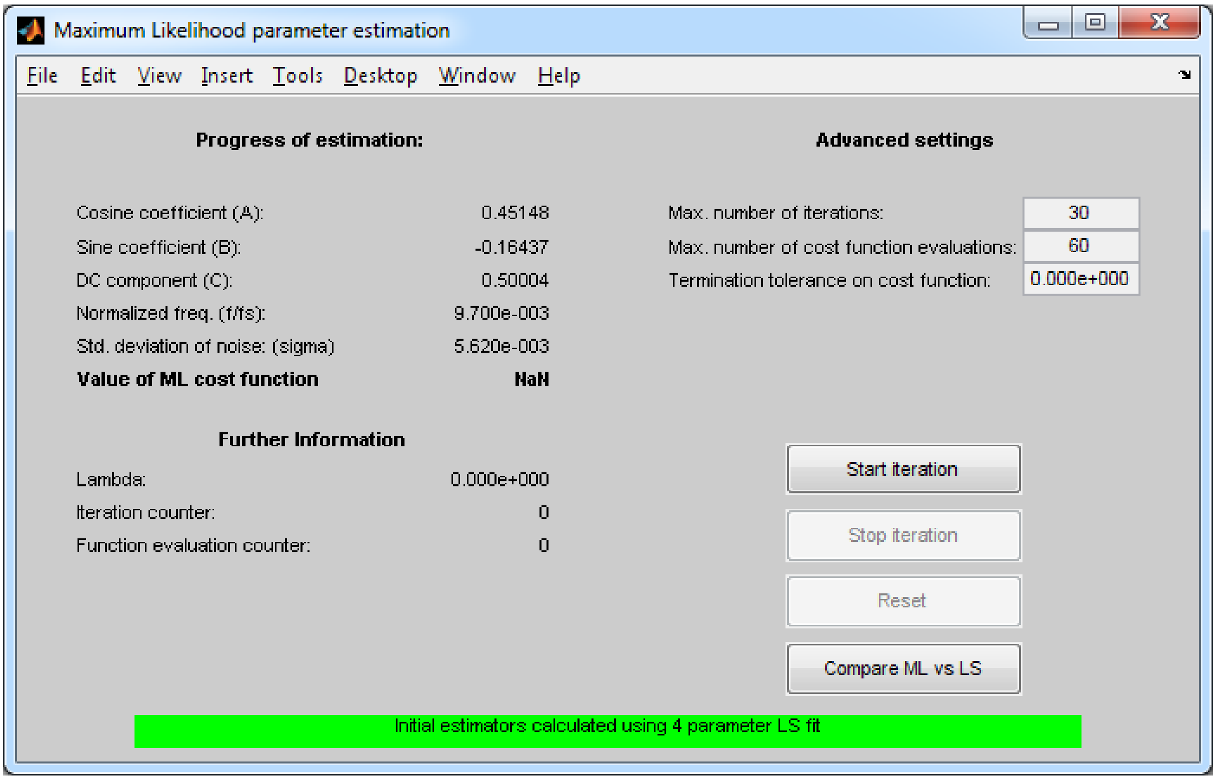
- **Mod T plot:** the residuals are sorted and displayed according to their location in the phase space. Phase axis is displayed between 0 and 2π. A reference sine wave is also plotted: this is a sine wave with the estimated phase of the excitation signal.
- **Histogram of residuals:** to observe statistical moments of the residuals.

5.3 Maximum likelihood estimation of signal and ADC parameters

To perform maximum likelihood (ML) estimation of signal and ADC parameters, it is necessary to use the so the results of histogram test, as the results of sine wave fitting in least squares (LS) sense. The histgram test provides the transition level estimators. Note that the transition level estimators do not change during the optimization, according to the problems described in [4]. Only the five signal parameters (four sine wave paramaters, and the standard deviation of noise on the input) are optimized, keeping the transition levels constant. If the histogram is rough according to the low number of samples in a record, the transition level estimators can be inaccurate. The main source of inaccuracy of ML signal parameter estimators is the inaccuracy of transition levels. Before performing ML optimization make sure that there are enough number of samples in record using the formula described in [3].
The LS sine wave fitting is used to get initial estimators of the sine wave parameters efficiently.

5.3.1 Getting initial signal parameter estimators

Although the result of this LS fitting is used only to start the ML optimization the parameters of this fitting also must be set. This dialog box is very similar to the one shown in 5.2. Both the input GUI elements and their function are the same. Note that the samples that are thrown beacuse of the amplitude or time limits will not be considered neither in the LS nor in the ML fit. The initial estimators appear in the dialog box of ML estimation before the iteration is started (figure 9).



Progress of estimation:

Cosine coefficient (A): 0.45148
Sine coefficient (B): -0.16437
DC component (C): 0.50004
Normalized freq. (f/fs): 9.700e-003
Std. deviation of noise: (sigma) 5.620e-003
Value of ML cost function NaN

Further Information

Lambda: 0.000e+000
Iteration counter: 0
Function evaluation counter: 0

Advanced settings

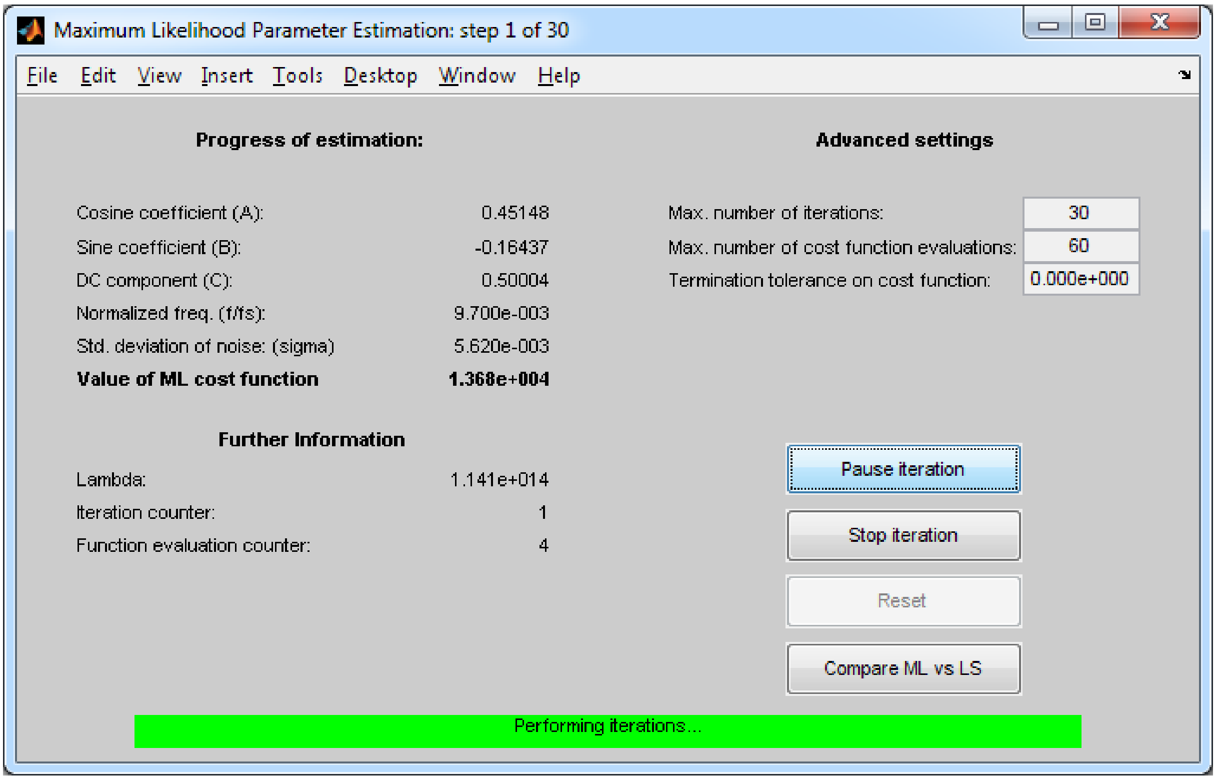
Max. number of iterations: 30
Max. number of cost function evaluations: 60
Termination tolerance on cost function: 0.000e+000

Initial estimators calculated using 4 parameter LS fit

Figure 9: ML estimation dialog box before the iteration is started

5.3.2 Progress of optimization: iteration cycles

The iteration can be started in the ML estimation dialog box using the "Start" pushbutton. The changed dialog box is shown on figure 10.


Maximum Likelihood Parameter Estimation: step 1 of 30
File Edit View Insert Tools Desktop Window Help
Pause iteration
Stop iteration
Reset
Compare ML vs LS
Performing iterations...

Progress of estimation:

Cosine coefficient (A):	0.45148
Sine coefficient (B):	-0.16437
DC component (C):	0.50004
Normalized freq. (f/fs):	9.700e-003
Std. deviation of noise: (sigma)	5.620e-003
Value of ML cost function	**1.368e+004**

Further Information

Lambda:	1.141e+014
Iteration counter:	1
Function evaluation counter:	4

Advanced settings

Max. number of iterations:	30
Max. number of cost function evaluations:	60
Termination tolerance on cost function:	0.000e+000

Figure 10: ML estimation dialog box during the iteration

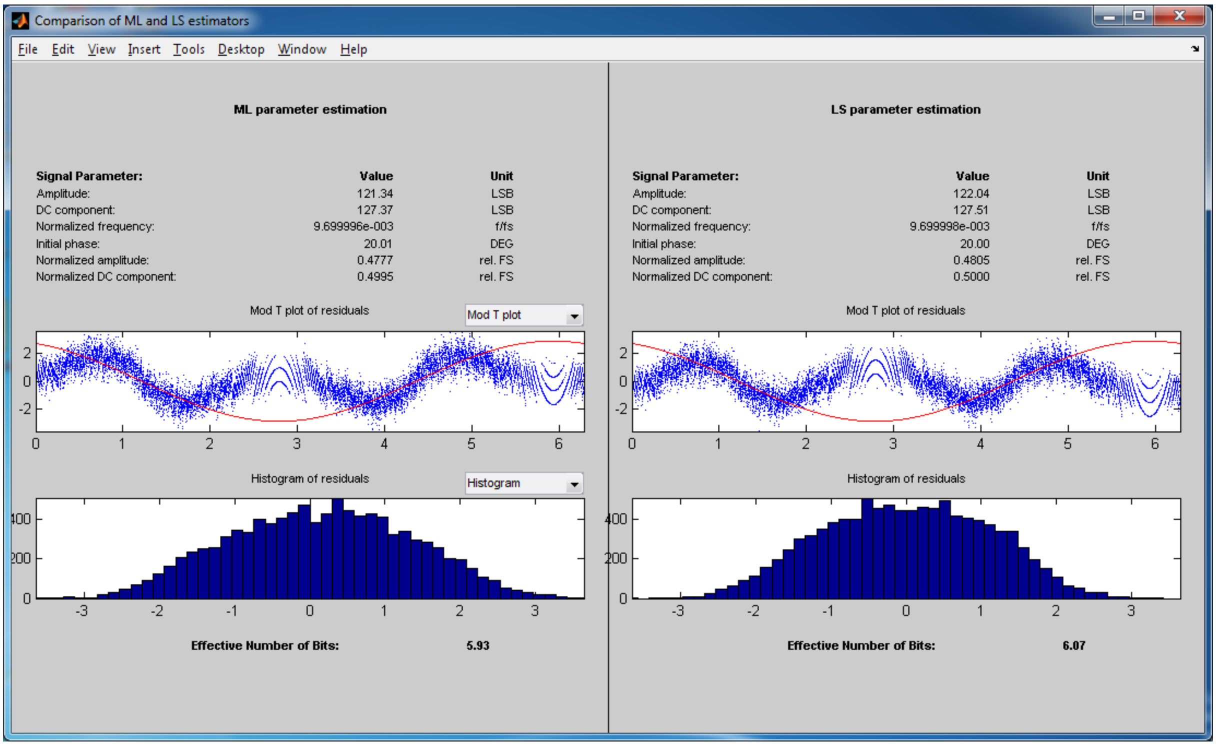
During the computation, the label and the function of this pushbutton changes to "Pause". The "Stop iteration" button is used to stop entire the optimization process. The "Reset" button resets the signal parameters to the initial values, and parameters of optimization can be set to other values. The advanced settings are the following:

- **Maximum number of iterations:** used to limit length of optimization.
- **Maximum number of cost function evaluations:** the length of an iteration cycle is not deterministic: depending on the behavior of the cost function there may be one ore more function and derivative evaluation in an iteration cycle. Limiting the number of function evaluations provides more precise time boundary.
- **Termination tolerance on cost function:** optimization terminates when the difference between the cost function in two consecutive iteration cycle is less than the tolerance specified here.

In the dialog box the the process of optimization can be traced. The actual values of parameter estimators, and the value of ML cost function is displayed in each iteration cycle. The constant that determines the size and direction of the Levenberg-Marquardt step ("lambda"), and the number of iterations and cost function evaluations also appear.

5.3.3 Results of optimizitaion: comparison of ML and LS estimators

After the optimization is performed both the LS and ML signal parameter estimators are available. The results can be compared in the results window shown on figure 11.



ML parameter estimation

Signal Parameter:	Value	Unit
Amplitude:	121.34	LSB
DC component:	127.37	LSB
Normalized frequency:	9.699996e-003	f/fs
Initial phase:	20.01	DEG
Normalized amplitude:	0.4777	rel. FS
Normalized DC component:	0.4995	rel. FS

Effective Number of Bits: 5.93

LS parameter estimation

Signal Parameter:	Value	Unit
Amplitude:	122.04	LSB
DC component:	127.51	LSB
Normalized frequency:	9.699998e-003	f/fs
Initial phase:	20.00	DEG
Normalized amplitude:	0.4805	rel. FS
Normalized DC component:	0.5000	rel. FS

Effective Number of Bits: 6.07

Figure 11: Comparison of ML and LS estimators

In this dialog box the estimated signal and ADC parameters appear. The amplitude and the DC component is displayed in ADC code units (LSB), and also in the percentage of the full scale (FS). The initial phase is displayed in degrees. The frequency of the sine wave is displayed relative to the sampling frequency. The effective number of bits (ENOB) is calculated using the difference between the record and the fitted sine wave (the residuals). **Note that the ENOB calculated using the ML estimators cannot be higher than the ENOB calculated using the LS estimators, because the LS optimization minimizies the root mean square of the residuals, thus maximizes the ENOB value.**

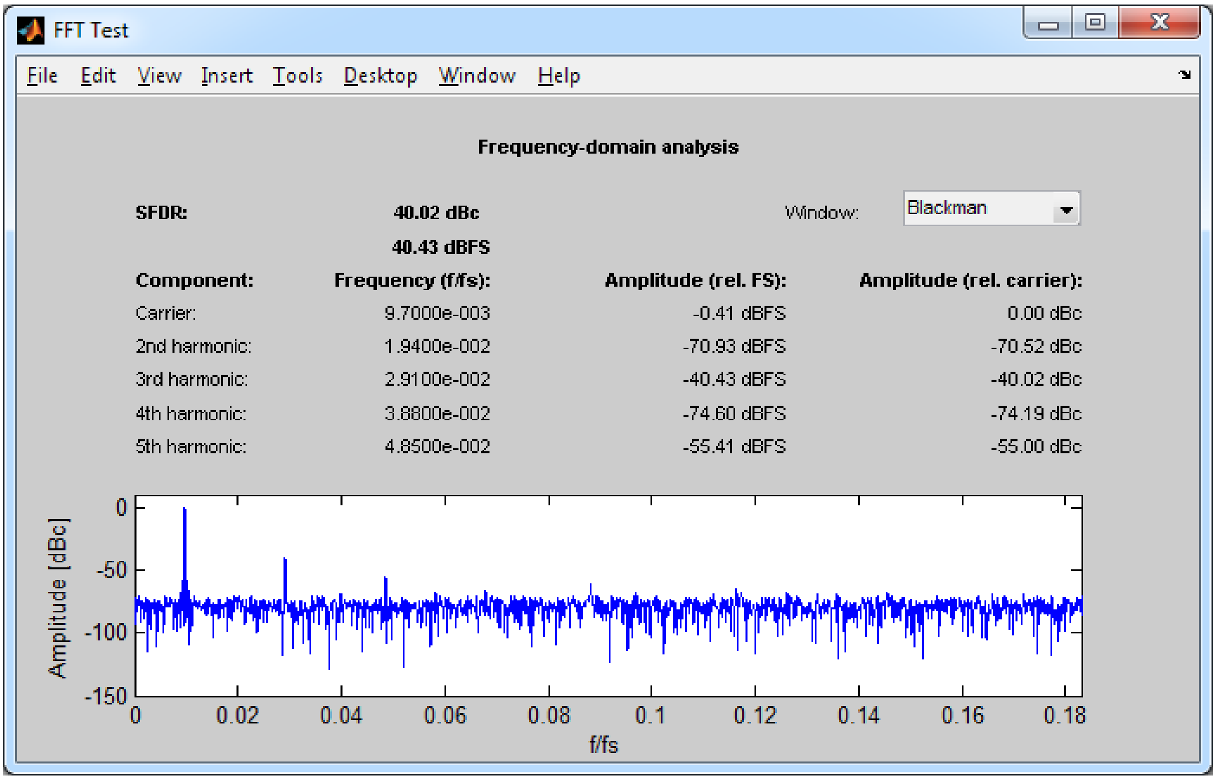
The residuals are displayed three ways in this window:

- **Residuals in linear time:** the residuals are displayed according to their position in the record.
- **Mod T plot of residuals:** the residuals are displayed according to their position in the phase space: phase position of each residual is calculated using the estimated frequency of the signal, and residuals are sorted with respect to this phase value. A reference sine wave is also diaplayed: the initial phase of this this sine wave is the estimated initial phase of the excitation signal.
- **Histogram of residuals:** histogram is calculated to observe statistical moments of residuals.

The linear time and the mod T plot of residuals do not appear in the same time: the content of the higher graph can be switched using a popup menu on the side of ML estimation. This switch changes the appearance of both sides of the window.

5.4 FFT test: analysis in the frequency domain

The frequency domain analysis investigates the Discrete Fourier Transform of the measurement record. DFT is performed using the Fast Fourier Transform (FFT) algorithm. Windowing in time domain is necessary to suppress spectral leakage in case of incoherent sampling. The user can specify the type of window: the default is the *Blackman* window, but also *Hann* and *3-term Blackman-Harris* windows can be applied. FFT test can be performed without windowing, choosing the *None (rect)* option.
The results provide information about the amplitudes and frequencies of the harmonics of the signal (up to 5 harmonics) relative to the carrier (base harmonic) and relative to the full scale of the ADC. The most important quantity calculated this way is the **Spurious-free dynamic range (SFDR)**, that is provided relative to the carrier (*dBc*), and relative to the full scale (*dBFS*).



Frequency-domain analysis

SFDR: **40.02 dBc**
40.43 dBFS

Window: Blackman

Component:	**Frequency (f/fs):**	**Amplitude (rel. FS):**	**Amplitude (rel. carrier):**
Carrier:	9.7000e-003	-0.41 dBFS	0.00 dBc
2nd harmonic:	1.9400e-002	-70.93 dBFS	-70.52 dBc
3rd harmonic:	2.9100e-002	-40.43 dBFS	-40.02 dBc
4th harmonic:	3.8800e-002	-74.60 dBFS	-74.19 dBc
5th harmonic:	4.8500e-002	-55.41 dBFS	-55.00 dBc

Figure 12: FFT test results window

References

[1] IEEE Standard for Terminology and Test Methods for Analog-to-Digital Converters

[2] Laśzló Balogh, István Kollár, Attila Sárhegyi, *Maximum Likelihood Estimation of ADC parameters*, Instrumentation and Measurement Technology Conference - IMTC 2010, Austin, USA, May 3-6, 2010

[3] Jerome Blair, *Histogram Measurement of ADC nonlinerities Using Sine Waves*, IEEE Transactions on Instrumentation and Measurement Vol 43., No. 3. June 1994

[4] Tamás Virosztek, *MATLAB-based ADC testing with sinusoidal excitation signal* (in Hungarian), B.Sc. Thesis, 2011.

[5] ADCTest project site: http://www.mit.bme.hu/projects/adctest