Harmonic distortion and statistical analysis

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Summary: *The measurement of harmonics terms on two identical digital receivers with fast ADC (AD6644) is presented and statistically analyzed. The results are discussed according to the origin of harmonics and difference between spurious and harmonics.*

Keywords: harmonic distortion, spurious, statistical analysis

Non-linearity and harmonic distortion

The high dynamic systems are limited before all by harmonic and spurious signals. Post-processing can eliminate the noise and present systems can achieve, according to the noise, the dynamic range as high as 150 dBFS/Hz. The harmonic amplitudes are mostly higher than -100 dBFS. That is why the origins of harmonic and the difference between harmonic and spurious are important.

More articles deal with ADC non-linearity and harmonic distortions. The model given by nonlinear dynamic system, linear dynamic system and nonlinear static system is presented as the possibility in [1]. It does not represent any deeper analysis; the aim of the article is to show up a set of problems that should gain the attention of the researchers. The INL from harmonic amplitudes is computed in [2]. The presented results are very good and the agreement with INL measured by a histogram test is excellent. It is a pity that the conditions of the measurement and used ADC are not described, that the reproducibility is not discussed, and before all that the test with different levels of input amplitude is not presented. The same point of view was presented in [3], but again without parameters of measurement. Some important remark is in this article that the scales of the measured and computed INL correspond badly. The presented results in [2] look very promising and we can make the conclusion that the dominant ADC nonlinearity is static INL. But only number of bits is there as the definition of the tested ADC. So the missing measurement parameters, missing definition of tested ADC and before all missing test with different input amplitudes open the doubt about general validity of such conclusion.

The validity of the m-th order law we tested in [4]. This law is used at analog circuits and helps to predict the change of output harmonic amplitude if the input signal changes its amplitude. We present the analysis, simulation and the measurement of itermodulations products. The simulations have given good agreement with the analysis, but the results of the measurement did not agree with theoretical analysis. The reasons can be more, as: spurious, dynamic nonlinearity, neglected dynamic ADC parameters, coupling between the analog and digital part, or some other unknown reason. A deeper analysis was not possible; we measured only amplitudes and not the phases of harmonic. Moreover, dynamic nonlinearity was at this ADC (AD872), given by sample-and-hold circuit.

Measurement

The home made digital receiver with ADC AD6644 and very low coupling between digital and analog part was used as an acquisition unit. The amplitude and phase of harmonic products as a function of input signal amplitude was measured. The amplitude of input filtered harmonic signal was changed with 1 dB step from FS–13 dB to FS –3 dB. Every measurement was repeated 10 times to test the short-term reproducibility and then repeated the next day to test the setting of measurement parameters and long-term reproducibility. Two identical systems were tested concurrently. The presented results were received with coherent sampling, fs=40 MHz. The filtered output from the PTS synthesizer was used as an input signal. Its frequency was of 61.5625 MHz. The harmonic from 2 to 7 were measured; theirs residual levels in input signals were -94; -90; -122; -123; -158; -131 dBc.

Results

The test on phase stability is presented in Fig 1. The phase of basic harmonic was measured at the output of both receivers. The difference of their phases is presented. Marks ‘x’ correspond to first measurements (10 times), marks ‘o’ correspond to the measurements the second day (5 times). The phase wander was lower than 0.15 .

In Fig 2 mean levels of output amplitudes and mean levels of output phases are presented as functions of input amplitude. The marks (‘ '; 'o'; ‘*'; ' '; 'x'; ' ') represent harmonic terms from 2 to 7. Mean levels were computed from 15 measurements. In Fig. 3 the corresponding error bar graphs for receiver A and harmonics from 2 to 4 are shown.

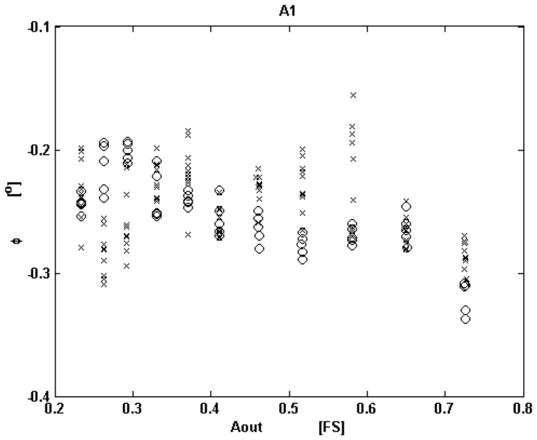
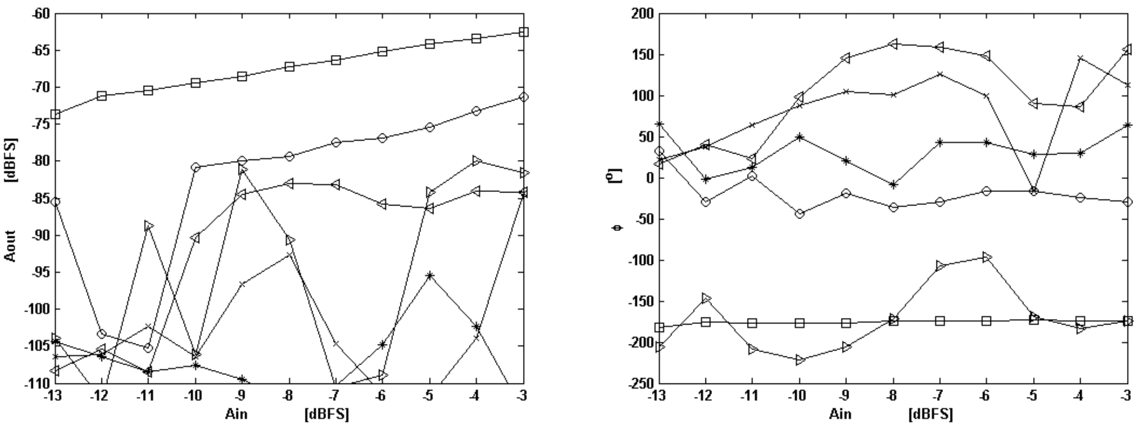


Fig 1. The phase wanders between the receivers. Marks ‘x’ represent first measurements, marks ‘o’ are for the second measurements.

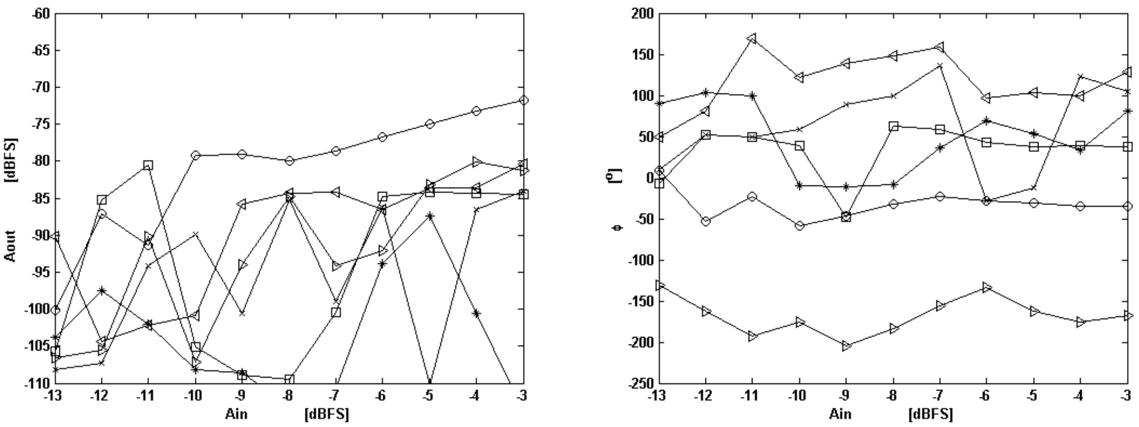
Statistical analysis

Scatter plot, a simple plot of one variable against another, gives the best view of parameters reproducibility, statistical distribution, and correlation between parameters. The advantages occur, if the contour ellipse, that expresses the 95% confidence interval, completes the plot. The relationship between the amplitude and phase for 2. and 3. harmonic for the receiver A) is in Fig. 4. The marks ‘*’ correspond to the first measurement, marks ‘o’ to second measurement. Both mean levels are determined by the input signal. The longer axis of ellipse coincides with the orthogonal regression line and in this case is parallel with Y-axis. So there exists no correlation between the phase error and the amplitude error.

The symmetry between the receivers is analyzed in Fig 5. by scatter plots for the input signal from –3 dBFS to –7 dBFS. Marks ‘*’ and full line correspond to the receiver A, marks ‘o’ and the dotted line to the receiver B.



Receiver A



Receiver B

Fig.2. Mean levels of output amplitudes and phases as functions of input amplitude. Marks (‘ '; 'o'; ‘*'; ' '; 'x'; ' ') represent harmonics terms from 2 to 7.

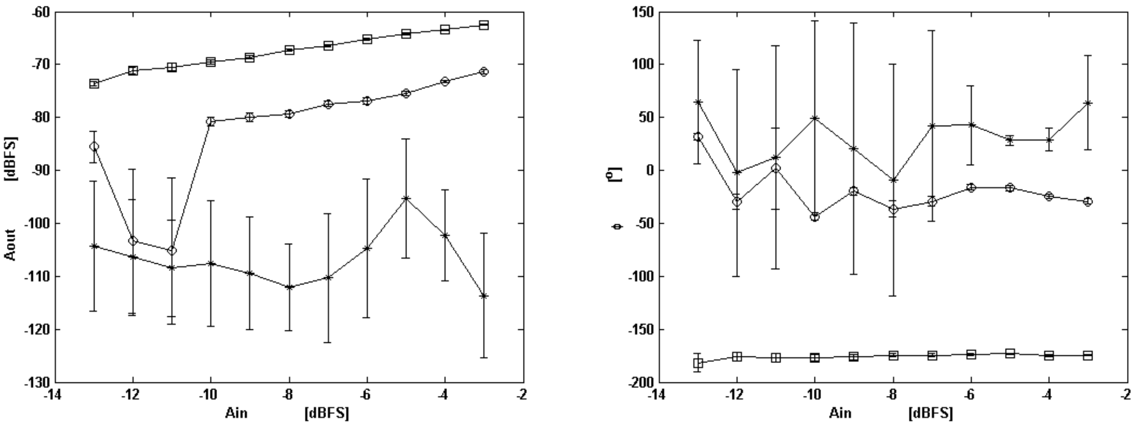
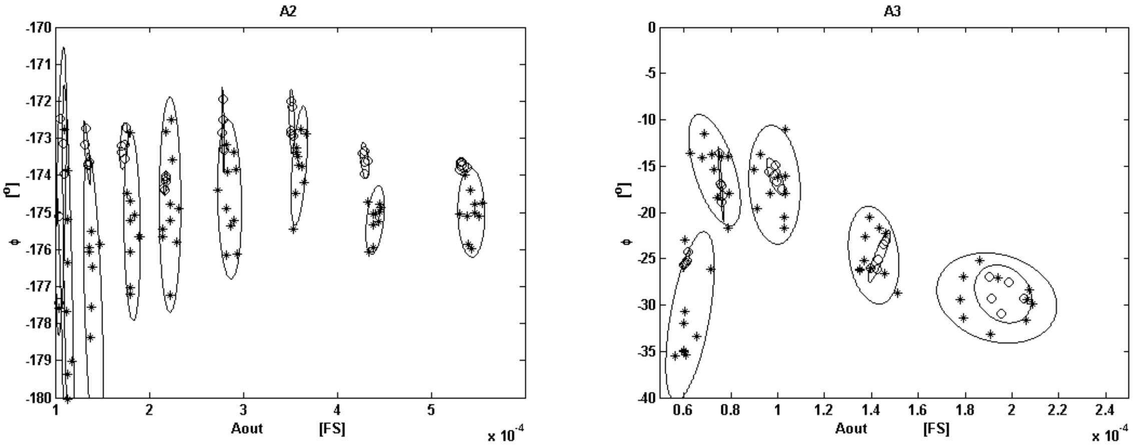
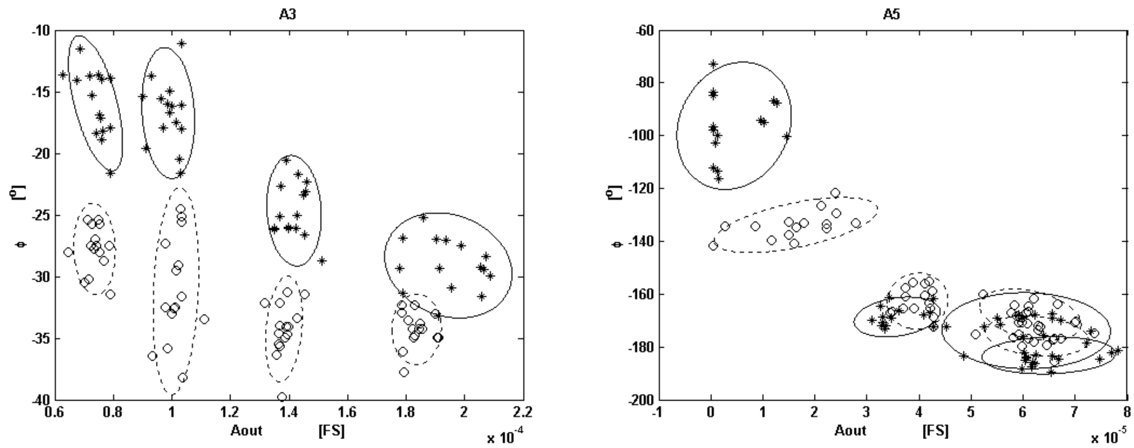


Fig. 3 Error bar graph for receiver A and harmonics from 2 to 4. Corresponding marks are: ‘ '; 'o'; ‘*'.



a) Receiver A), second harmonic. b) Receiver A), third harmonics.

Fig. 4. Scatter plots; the dependency between phase and amplitude. Marks ‘*’ correspond to the first measurement, marks ‘o’ to the second measurement.



a) Third harmonic b) Fifth harmonic

Fig. 5. Symmetry between receivers represented as the amplitude of harmonic versus phase for input signal from –3 dBFS to –7 dBFS. Marks ‘*’ and full line receiver A, marks ‘o’ and dotted line receiver B.

Discussion

a) Reproducibility: The long term reproducibility of measurement is good, if the corresponding harmonic has the amplitude higher than –85 dBFS. If the amplitude is lower, the reproducibility decreases and moreover, the amplitude and phase as the functions of input amplitude change randomly. The level –85 dBFS does not correspond with the noise level (it was –135 dBFS) or with the stability of input signal. The long term phase wander was lower than 0.15 ; and the standard deviation of the relative input amplitude was 0.01%. At second and third harmonics we can suppose some relation with the residual levels of harmonics in the input signals (-94 and –90 dBc), but the same impact we can see at the fifth harmonics, where the residual level is –123 dBc.

b) Symmetry between the receivers A, B: The odd harmonics (3,5,7) with the amplitude higher than –85 dBFS have roughly equivalent dependency of amplitude and phase on input signal. Even harmonics terms in the receivers A and B are different.

c) The validity of m-th order law: In this case the INL should be the main source of harmonic products and if the input signal changes its amplitude for one dB, the m-th harmonics should change its amplitude for m dB. This is not valid at all. The amplitudes change roughly for the same dB level as an input signal (receiver A harmonics 2 and 3; receiver B harmonics 3); or they are roughly constant and do not depend on the input signal (harmonics 5 and 7 at both receivers); or change randomly (amplitudes lower than –85 dBFS). The conclusion is that in this case the INL is not the main source of harmonic signals.

d) Phase: The output phase of harmonics terms given by nonlinear static system should be zero. Some constant phase shift can be given by the linear dynamic system that will be over the nonlinear static system. According to our measurement the phase of harmonic is constant, if the corresponding harmonic has amplitude higher than –85 dBFS. If the amplitude is lower and changes randomly with input signal, also the phase is changed randomly.

e) Statistical analysis: It is a pity that statistical analysis is mostly neglected at ADC test and measurement. In our opinion the measurement and analysis of harmonic and spurious has no sense without statistical analysis. The contribution of one-dimensional statistical methods is low; the multidimensional methods should be used. We have a good experience with scatter plots and confidence ellipses. This graphical presentation was very useful as we analyzed the correlation and reproducibility.

f) Harmonic versus spurious: Some exact definition of harmonic and spurious is missing. The difference given only by the frequency of discreet signal is insufficient. The rules used at analog circuits as m-th order law are not generally valid at ADC and digital systems. The spurious are in reality the determined signals as well. Only the change of their amplitude and phase cannot be predicted from the change of the input signal. This is also valid at our receivers if the output harmonic amplitude is lower than –85 dBFS.

g) Origin of harmonic: We can say only, that the main origin of harmonic at measured receivers is not INL. The m-th order law is not valid. The possible sources are: DNL, quantization and insufficient input noise, coupling between digital and analog parts, insufficient decoupling of power supplies, digital processing. All this sources also produce spurious. More measurements must be done to determine the main origin of harmonics.

Conclusion

Important questions at the design of any high dynamic range system are: origins of harmonic and spurious signals; the differences between them; how to minimize them. But these areas are neglected not only in the drafts of ADC standards but also in ADC articles. We would like to attract the attention to this area; many questions are still open. We intend to continue in some other measurements, as the dependence on coherent and non-coherent sampling or on input frequency.

Acknowledgement: The work was supported by the grant of Grant Agency of the Czech Republic No. 102/02/0553.

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