Posteriori Frequency Spectrum Correction for Test Signal Imperfections in ADC Testing at 1MHz – Practical Experience

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Abstract- In the last several years, many high-resolution and high-speed ADCs have appeared on the market. Since the signal purity of commercial generators particularly at MHz frequencies has not essentially increased in the same period, the problem of how to test ADCs has rose. This fact initiated the research of alternative methods based on either the application of special signals or posteriori correction of the measured sine-wave signal [1]. The latter method concerning a simple correction in the frequency domain was analyzed in [2], extended and practically applied in [3]. The application and the results of this extended method at the frequency of 1 MHz are presented in this paper.

I. Proposed approach

The method of frequency spectrum correction introduced in [2] is based on two different measurements by the tested ADC (see Fig. 1) and posteriori computation of generator and ADC harmonic distortion. The signal produced by a common harmonic generator, $G(j\omega)$, is filtered by one of two filters with different frequency characteristics, $F(j\omega)$, $H(j\omega)$, and the signal on filter output, $X(j\omega)$, is measured by the tested ADC. When both filters are linear and have the same amplitude frequency characteristics (attenuation) at the fundamental frequency, the same ADC harmonic distortion[1], $D(j\omega)$, is added to generator harmonic distortion modified by filters in both measurements. ADC harmonic distortion can be derived from the frequency spectra, $Y_1(j\omega)$, $Y_2(j\omega)$, computed in each measurement using the formulas

$$Y_1(j\omega) = F(j\omega)G(j\omega) + D(j\omega), \qquad (1)$$

$$Y_2(j\omega) = H(j\omega)G(j\omega) + D(j\omega). \qquad (2)$$

Distortion induced by the test signal can be either correlated or uncorrelated with the ADC distortion. When external disturbance affecting both the test signal and the ADC is avoided, the correlated distortion is restricted only to harmonic distortion. The analysis mentioned above (based on [2]) was performed only on this type of distortion; uncorrelated distortion was introduced in [3]. In case of uncorrelated distortion, power of the signal measured by the ADC at any nonharmonic frequency is given by the sum of powers of the test signal distortion and ADC distortion at the same frequencies. This fact can be described by

$$\mathrm{E}\left\{\left|Y_1(j\omega)\right|^2\right\} = \left|F(j\omega)\right|^2 \mathrm{E}\left\{\left|G(j\omega)\right|^2\right\} + \left|D(j\omega)\right|^2, \qquad (3)$$

$$\mathrm{E}\left\{\left|Y_2(j\omega)\right|^2\right\} = \left|H(j\omega)\right|^2 \mathrm{E}\left\{\left|G(j\omega)\right|^2\right\} + \left|D(j\omega)\right|^2 \qquad (4)$$

for the first and second measurement according to Fig. 1 where E{} is the expectation operator. The derivation of expression $D(j\omega)$ from (1) and (2) and $|D(j\omega)|$ from (3) and (4) is straightforward.

Frequency spectrum corresponding only to the tested ADC can be theoretically completely reconstructed using the formulas above. In practice, correction efficiency is limited by measurement accuracy of all frequency spectra and also by the amount of needed correction because the more correction is needed, the lower accuracy can be reached. Since noise has stochastic character, averaging in frequency domain has to be applied so that mean values in (3) and (4) can be computed. The averaging also increases measurement precision.

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[1] For the simplicity, ADC distortion, $D(j\omega)$, and the output signal, $Y(j\omega)$, are expressed in the continuous frequency domain.

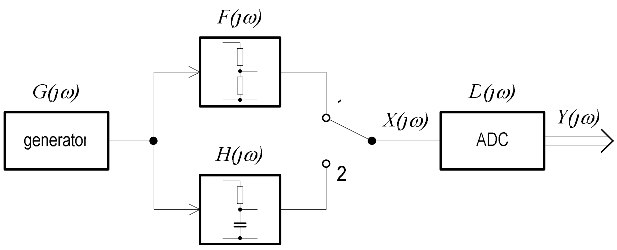


Fig. 1 Block diagram of the measurement setup

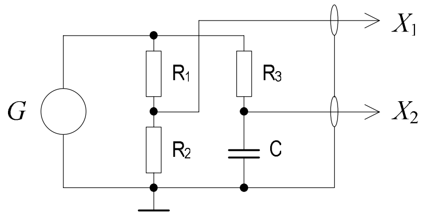


Fig. 2 Schematic of the measurement setup

II. Experimental measurements

Practical verification of the proposed method presented in [3] was performed on a real 3-channel, low noise, low power 24-bit Σ-Δ ADC AD7793 at the sampling frequency of 500 Hz and input signal frequency of 27.145 Hz. ADC input was set to high impedance; consequently, it was not needed to be incorporated in calculations. Since no other suitable generator was at disposal, low-distortion signal generator, SR DS 360 was applied. Generator's output sine-wave signal was additionally distorted by nonlinearity and one spurious component was added. So, the test signal was only an approach to that of common commercial generators.

Therefore, the proposed method was further applied for more practical situation. The tested device consisted of two top PXI digitizers, PXI NI-5122 and PXI NI-5922, running at the sampling frequency of 10 MHz; input sine-wave signal 1.053 MHz was produced by common HP 33120 (for PXI NI-5122 testing) and Agilent 33250 (for PXI NI-5922 testing) generators and both testing filters were designed with regard to impedance matching (50 Ω) of all signals.

The last test condition on measurement setup was the most difficult to be fulfilled. Input or output impedance of devices (generator, ADC) is commonly not accurately adjusted and its complex character is also not exactly known. But, any impedance mishmash can induce errors that can essentially reduce the correction accuracy due to changed transfer function of both filters.

Testing filters were designed for the simplest test setup. This leads to resistor attenuator and RC filter (see Fig. 2). Note that the combination of an attenuator and RC filter does not fulfil the condition of different frequency characteristics of both filters at low frequencies; this will theoretically result in the increase of errors. The design of both filters was performed with regard to only two conditions: impedance matching of all signals and the same absolute value of transfer function at the tested frequency. This leads to simultaneous equations with only one solution:

$$\begin{aligned} R_1 &= 60.64\ \Omega, \quad R_2 = 106.0\ \Omega, \\ R_3 &= 73.37\ \Omega, \quad C = 2.666\ \text{nF}. \end{aligned} \tag{7}$$

Each resistor was practically realized as a serial-parallel combination of several discrete resistors in order to equally distribute the power dissipation and consequently to minimize the nonlinearity of each discrete resistor. The capacitor was also composed of several discrete mica capacitors with high linearity. The linearity of all components is very important so that no higher harmonic components are produced by the filters; therefore, common ceramic capacitors cannot be applied. Possible nonlinearity of filters could be theoretically corrected similarly like test signal harmonic distortion; but it would complicate the computations and decrease the accuracy.

For the computation of ADC distortion, the transfer function of the RC low-pass filter, $H(j\omega)$, is needed. Theoretically, it could be determined by the formula

$$H(j\omega) = \frac{1}{1 + j\omega R_3 C}\ ; \tag{8}$$

nevertheless, due to parasitic characteristics of filter components, the theoretical formula would not be exact enough. Thus, filter characteristics has to be measured first.

The most important points of filter characteristics for this method are harmonic frequencies of the input signal. So, the ideal test signal should contain strong components at integer multiples of the fundamental—e.g. saw signal. If signal amplitudes at measured frequencies are strong enough, ADC distortion is negligible and the tested ADC can be applied even for the filter characteristics measurement.

The frequency of saw signal was set to one twentieth of the fundamental because of the frequency limitation of HP 33120 generator. The output signal was measured on X_1 and X_2 outputs with saw input signal. Noise variance in frequency spectra was decreased by frequency spectrum averaging (Welch method) with the overlapping of 50 %.

Amplitude frequency characteristics of RC filter was computed from the measured frequency spectra as

$$|H(j\omega_h)| = |X_2(j\omega_h)| - 2|X_1(j\omega_h)| \tag{9}$$

and its phase frequency characteristics $\Delta\phi$ as

$$\Delta\phi(H(j\omega_h)) = \Delta\phi(X_2(j\omega_h)) - \Delta\phi(X_1(j\omega_h)) \tag{10}$$

at harmonic frequencies, ω_h, of rectangular fundamental. All phases were determined relatively to the fundamental phase (see [4] for more details about relative phase determination).

The frequency characteristics of the resistor attenuator should be measured at the test frequency so that possible parasitic impedances could be taken into account, too. But, an ideal resistor attenuator was considered in this experiment assuming a negligible influence of parasitic impedances. At higher frequencies, particularly, the phase shift of this filter is needed to be known for achieving good measurement accuracy.

In the second step, a sine wave generator was applied in the measurement setup and output signals on X_1 and X_2 outputs were measured by the tested ADCs (see Fig. 3a,c). 256k-point FFTs were computed in case of PXI NI-5122 digitizer and 16k-point FFTs in case of PXI NI-5922 digitizer. Amplitude frequency spectra in Fig. 3b,e were computed by applying the frequency spectrum correction method at harmonic as well as nonharmonic frequencies. Since the filter characteristics was measured only at several frequencies, polynomial interpolation was applied for the correction at other frequencies in (3), (4).

For the purpose of result verification, ADC amplitude frequency spectrum was also measured with high-purity sine wave signal (see Fig. 3c,f). Magnitudes M and relative phases $\Delta\varphi$ of the harmonic components computed from each frequency spectrum with sine wave input are summarized in Table 1,2.

The results showed that harmonic components were effectively corrected. Considering that the correction of up to 40 dB was made (PXI NI-5122, the 3rd harmonic component), result errors were relatively low. The errors were mainly caused by impedance mishmash and instabilities of measurement components.

The effectiveness of noise correction was worse. The highest errors appeared bellow second harmonic components where filter characteristics $F(j\omega)$ and $H(j\omega)$ did not differ enough. Noise correction above this frequency was quite successful. Nevertheless, noise correction can never be as effective as harmonic distortion correction because of its stochastic character.

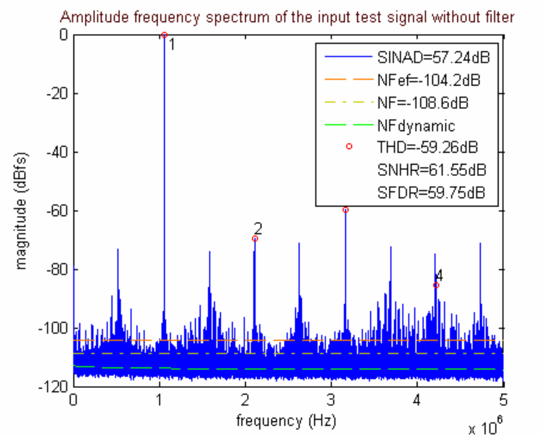
The uncorrected noise appears in the amplitude frequency spectrum particularly at low frequencies and also in a close vicinity of the fundamental. The noise in both regions worsens the computed ADC parameters such as the *SINAD* or *SNHR*. Nevertheless, an additional correction (e.g. according to [5]) can significantly reduce at least the dominant close-to-fundamental noise and it enables to make a better estimate of these ADC parameters.

Table 1. Correction results, PXI NI-5122

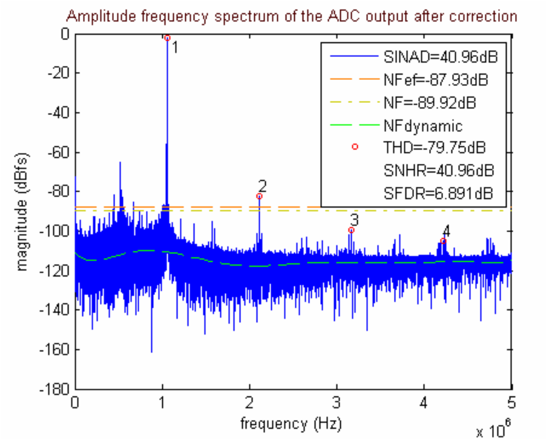
signal	parameter	harmonic component		
		2nd	3rd	4th
X_1	M (dBfs)	–69	–60	–85
	$\Delta\varphi$ (rad)	1.6	–1.8	2.6
X_2	M (dBfs)	–72	–64	–91
	$\Delta\varphi$ (rad)	1.6	–1.3	–2.7
corrected	M (dBfs)	–82	–99	–103
	$\Delta\varphi$ (rad)	0.31	–2.8	–1.0
high-purity	M (dBfs)	–84	–99	–101
	$\Delta\varphi$ (rad)	0.55	–2.4	–0.86

Table 2. Correction results, PXI NI-5922

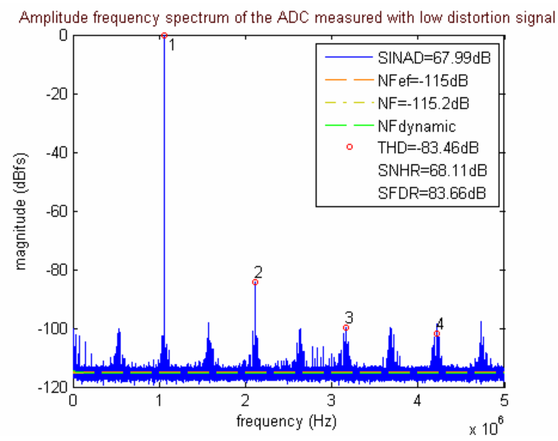
signal	parameter	harmonic component		
		2nd	3rd	4th
X_1	M (dBfs)	–77	–75	–94
	$\Delta\varphi$ (rad)	–0.36	–2.4	–1.9
X_2	M (dBfs)	–79	–80	–101
	$\Delta\varphi$ (rad)	–0.16	–2.0	–1.3
corrected	M (dBfs)	–89	–103	–110
	$\Delta\varphi$ (rad)	0.87	2.9	–2.2
high-purity	M (dBfs)	–92	–99	–113
	$\Delta\varphi$ (rad)	1.5	2.4	–1.7



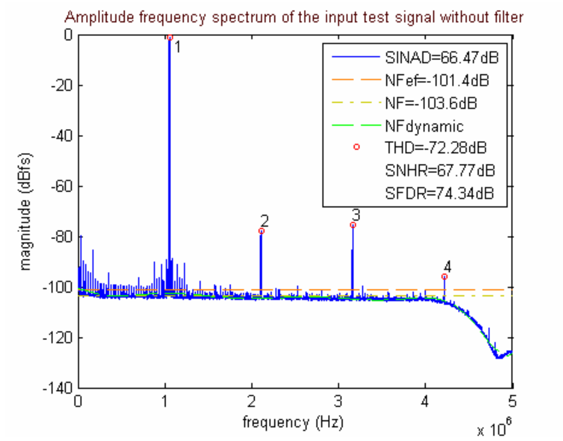
a) PXI NI-5122, input test sine-wave measured on X_1



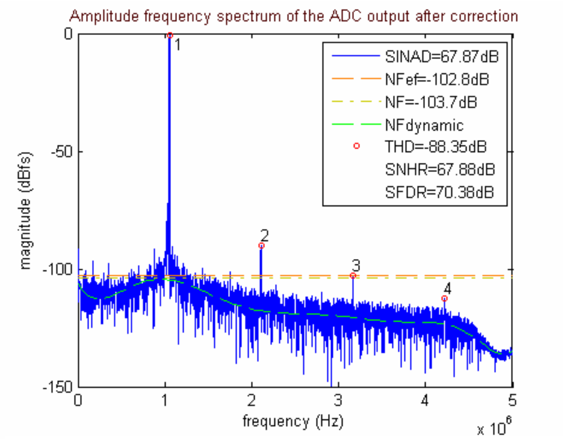
b) PXI NI-5122, computed by the correction method



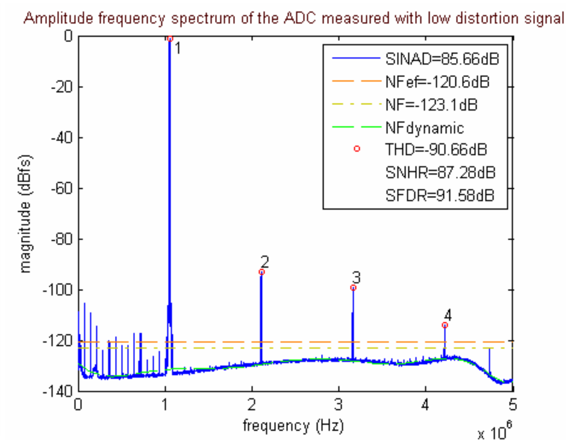
c) PXI NI-5122, measured with high-purity sine wave



d) PXI NI-5922, input test sine-wave measured on X_1



e) PXI NI-5922, computed by the correction method



f) PXI NI-5922, measured with high-purity sine wave

Fig. 3 Amplitude frequency spectra

III. Conclusion

The applicability of the proposed method was proved on practical measurements at the signal frequency of 1 MHz. Strong harmonic distortion of the test signal was successfully suppressed in the measured frequency spectra and the resulting ADC distortion was computed with a relatively low error. The correction of noise was not so effective particularly bellow the frequency of the second harmonic component. The reason of lower correction for test signal noise were too simple filters and also stochastic character of this signal component. Generally, the overall performance of this method could be increased by higher order filters that should be of band pass type in the best case.

References

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