

CAN BE ESTIMATED THE MEASUREMENT UNCERTAINTY OF DAQ SYSTEM FROM DATA SHEETS OF USED A/D MODULES?

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Abstract - The estimation of a measurement uncertainty of a sampled signal based on parameters of A/D modules published in data sheets is not already trivial. When a very low frequency (pseudo-static) signal is sampled, the static parameters, which are usually published by well-known producers can be used for this purpose. The more complicated situation arises in the case of a dynamic measurement, when the most of producers present only minimum of parameters. It is usually the total harmonic distortion (*THD*), or the analogue bandwidth for low and/or full scale signal. The most important dynamic parameters as the effective number of bits (*ENOB*), or the signal to noise and distortion (*SINAD*) including their frequency dependence are published very seldom.

Keywords: measurement uncertainty, A/D module, static parameter, dynamic parameter.

1. INTRODUCTION

The quality, the number and the connotation of the parameters published in data sheets of A/D modules (PC plug-in boards, PC Cards, CompactPCI boards, USB modules etc.) used in DAQ systems are very various by different producers. The resolution only is determined in the case of the most of low-cost products. In opposite, all of the well-known producers (National Instruments, Data

Translation, Keithley, Analogic, DATEL etc.) determine at least the static parameters. Unfortunately, there is no unification in the published parameters, their units and in the terminology (see Table 1). One of the producers used even different ways for describing some parameters for various types of A/D modules.

Much worse situation is in the area of parameters describing a dynamic quality of A/D modules. The most of producers present only the minimum of parameters, and some of them cannot be applied for the measurement uncertainty estimation.

2. MEASUREMENT UNCERTAINTY ESTIMATION

How to estimate the measurement uncertainty of a sampled signal based on the parameters published in data sheets will be mentioned below.

The transformation of the number of A/D module imperfections to undesirable components of the digital output signal (real noise, spurious components etc.) makes it possible to estimate the „total noise“ for an individual application. The „total noise“ can be applied in the number of simple cases as a „type A“ uncertainty, whereas the gain error, the offset and the integral non-linearity cause a „type B“ uncertainty by the estimation of the combined measurement uncertainty.

Table 1. Static parameters published in data sheets

	Nat. Instr.	Data Transl.	ANALOGIC	Keithley	IOtech
Gain error	% of reading	%FSR	%FSR	% of reading	%
Offset error	mV (μ V) *)	μ V	mV	LSB *)	μ V
Temperature drift of gain	% / °C	ppm FSR/°C	ppm FSR/°C	ppm FSR/°C	ppm / °C
Temperature drift of offset		μ V / °C	μ V / °C	μ V / °C	μ V / °C
Integral non-linearity	-	%FSR	%	-	%FSR
Noise (incl. quantization)	mV (μ V)	LSB+ μ V**)	LSB	LSB	-

	ADDI-DATA	DATAQ	QUATECH	DATEL	Advantech
Gain error	LSB	%	LSB (%FSR)	LSB	-
Offset error	LSB	mV	LSB	LSB	-
Temperature drift of gain	-	ppm / °C	-	LSB / °C	-
Temperature drift of offset	-		-	LSB / °C	-
Integral non-linearity	LSB	LSB	LSB	LSB	-
Noise (incl. quantization)			LSB		-

*) Offset error + Integral non-linearity

***) System noise + Amplifier Input Noise

The measurement uncertainty of the output value (for one sample) can be then estimated using the formula:

$$u_C = \sqrt{u_A^2 + u_B^2} \quad (1)$$

A general practice is to use the expanded uncertainty U for defining an interval, where the real value lies with the determined probability. Using the coverage factor $k=2$, then

$$U = 2u_C = 2\sqrt{u_A^2 + u_B^2} \quad (2)$$

2.1. Uncertainty Estimation for Static Measurement

The most of producers describes the static parameters of A/D modules using the gain error, the offset (occasionally also including their temperature drift), and the linearity error described by Integral Non-Linearity (*INL*). The similar way as for the uncertainty estimation using a digital voltmeter can be applied.¹

Then (if the temperature is in the defined range) the component u_B (in V) can be calculated using the formula

$$u_B = \frac{\delta_G X / 100 + \Delta_{\text{Off}} + \text{INL} \text{ FSR} / 100}{\sqrt{3}} \quad (3)$$

where: δ_G is the gain error in % of full scale input range,
 Δ_{Off} is the offset in V,
 INL is the integral non-linearity in % of FSR defined according [1],
 X is the measured value in V,
 FSR is the full scale input range in V.

If the temperature is outside of a defined range and the temperature drifts are presented, the formula (3) have to be modified respecting the temperature drift coefficients.

$$u_{B,\vartheta} = \sqrt{u_B^2 + \left(\frac{X \delta_{\vartheta G} \Delta_{\vartheta}}{100 \sqrt{3}} \right)^2 + \left(\frac{\Delta_{\vartheta \text{Off}} \Delta_{\vartheta}}{\sqrt{3}} \right)^2} \quad (4)$$

Table 2. Dynamic parameters published in data sheets

	Nat. Instr.	Data Tran.	ANALOGIC	DATEL	IMTEC	Gage
Crosstalk	Yes	Yes	Yes	Yes	Yes	Yes
Analogue input bandwidth	Yes *)	No	Yes	No	Yes	Yes
Signal to noise and dist. ratio	No	No		No	No	No
Effective number of bits	No	Yes		No	No	Yes
Signal-to-Noise Ratio	No	Yes	Yes	No	Yes	Yes
Total Harmonic Distortion	No	Yes	Yes	Yes	No	No
Spurious free dynamic range	No	No	Yes	No	No	No

*) Small signal: decrease of amplitude -3 dB, large signal: THD < -40 dB

¹ If the gain error, offset and INL are determined as maximal warranted values, then they have the same meaning as error of reading and error of range for DVM. If the upper and lower limits (maximal error) are known and there are no other specific knowledge about the possible values of errors within interval, a uniform distribution is presupposed [3].

where X is the measured value in V,
 $\delta_{\vartheta G}$ is the temperature drift of the gain in %/°C,
 $\Delta_{\vartheta \text{Off}}$ is the temperature drift of the offset in V/°C
 Δ_{ϑ} is the deviation of the outside temperature from the nominal value in °C

Some producers (National Instruments, Keithley, Data Translation) express the static parameters using another way in some cases. For instance, the first component of the parameter “Absolute Error” (published in data sheets of National Instruments) corresponds with the gain error, and the second one incorporates obviously the offset and *INL*.

The component u_A includes all other influences described by the noise (see above). The most of producers publish the parameter “RMS noise” or “System noise” (RMS value expressed usually in LSB) among the static parameters in the data sheet, because the components, which arises by the sampling a dynamic signal (e.g. due to a jitter etc.) are not included. If the noise is expressed in LSB, than the component u_A (in V) can be calculated using the formula

$$u_A = \text{Noise} \frac{\text{FSR}}{2^n - 1} \quad (5)$$

where: *Noise* is the “RMS noise” or “System noise” mentioned above and expressed in LSB,
 n is the number of bits of used A/D module,
 FSR is the full scale input range in V.

However, the measurement conditions are not presented here (EMC conditions in system case above all). The best way for an estimation of the real value of the component u_A is to short-circuit the analogue input of the module by a real operating condition, and to calculate the RMS value of the output signal.

An example of the measurement uncertainty estimation of one sample for the DC or very low frequency input signal (the frequency of an input signal is much smaller then the sampling frequency and the input bandwidth) is published in Appendix.

2.2. Uncertainty Estimation for Dynamic Measurement

The more complicated situation arises in the case of a dynamic measurement. Even some of well-known producers presented the **Total Harmonic Distortion (THD)** only,

corresponding usually with one input signal frequency, or an analogue bandwidth for the low level and/or full scale signal - see Table 2. There is no information about the frequency dependence of *THD* or the component of an output noise arising due to a jitter. Also a crosstalk between channels is

not always published. It complicates the measurement uncertainty estimation. The **Effective Number Of Bits - ENOB**, or the **Signal to Noise And Distortion - SINAD** (see [2]) including their frequency dependence are published very seldom.

When *THD* for the defined frequency and the bandwidth is published, the component u_B can be determined using the similar way as in the previous case, but *INL* of the A/D module is included in *THD*, and the frequency dependence of the gain must be taken into account. In this case the component u_{B1} contains the gain error including its frequency dependence and the offset. In the case, that the frequency bandwidth f_{BW} is defined using "classical" way (by the decrease of amplitude of 3 dB²) and the 1st order system is presupposed, the frequency dependence of gain is described for f smaller then about $0.4f_{BW}$ by:

$$G(f) = G_{DC} \sqrt{\frac{1}{1 + (f/f_{BW})^2}} \cong G_{DC} [1 - 0.5(f/f_{BW})^2] \quad (6)$$

where $G(f)$ is the gain by frequency f ,
 G_{DC} is the gain for DC input signal,
 f is the used frequency.

Then the gain error by the frequency f can be approximately described as

$$\delta_{G,f} = \delta_{G,DC} + 0.5(f/f_{BW})^2 \quad (7)$$

Also the phase error arises in this case, of course. It causes the further additional error, particularly the change of the shape of a non-sinusoidal waveform. Fortunately, it has a small effect only, if the RMS value, power etc. is measured and the same phase shift of all used channels is supposed.

The component u_{B2} includes *INL*, which is described by *THD*. Then

$$u_B = \sqrt{u_{B1}^2 + u_{B2}^2} \quad (8)$$

where:

$$u_{B1} = \left(\frac{\delta_{G,f} X / 100 + \Delta_{Off}}{\sqrt{3}} \right) \quad (V) \quad (9)$$

$$u_{B2} = \left(\frac{FSR}{2\sqrt{2}} 10^{\frac{THD}{20}} \right) \quad (V) \quad (10)$$

and Δ_{Off} , X , FSR have the same meaning as in (4),
 $\delta_{G,f}$ is defined by (7)
 THD is the total harmonic distortion defined according [1].

The component u_A includes all random components, e.g. the system noise described above and published usually as a static parameter, unfortunately without the noise arising due to the jitter.

If a multichannel measurement is applied, then crosstalk must be taken into account and the further component u_{B3} enters into the measurement uncertainty estimation. For the evaluated channel j (if other channels are used) is valid:

$$u_{B3} = \sum_{ch=1} \left(\frac{10^{\frac{CT}{20}} FSR_i}{2\sqrt{2}} \right) \quad (V) \quad (11)$$

where CT is the value of the crosstalk in dB,
 FSR is the the full scale input range (in V) of the other used channels $i \neq j$,
 ch is the number of all used channels,

In the case, that *ENOB* or *SINAD* (including their frequency dependence) and all other parameters mentioned above are published, the measurement uncertainty can be estimated also for an input signal with higher frequency, where also the influence of the jitter comes in. As *ENOB* and *SINAD* includes both the deterministic (*THD*) and the random parts (all components of noise), the combined measurement uncertainty u_c (without a separation of the components u_A and u_B) can be estimated using the formula

$$u_c = \sqrt{u_{B1}^2 + \left(\frac{FSR}{2\sqrt{2}} 10^{\frac{-SINAD}{20}} \right)^2 + u_{B3}^2} \quad (V) \quad (12)$$

where u_{B1} is defined by (9),
 u_{B3} is defined by (11),
 FSR is the full scale input range of the used channel in V.

The third component will be applied only, if the multichannel mode is used. If *ENOB* is published, than $SINAD = 6.02 ENOB + 1.76$ [2].

An example of the measurement uncertainty estimation of one sample by the dynamic signal sampling is published in Appendix.

Unfortunately, the producers of A/D modules publish the values of *ENOB* or *SINAD* very seldom (exception Data Translation for instance) and only for several isolated frequencies of the input signal. Sometimes the other dynamic parameters are published, e.g. a **Spurious Free Dynamic Range (SFDR)** etc.

3. CONCLUSION

The static parameters, which are published in data sheets of well-known producers usually enables to estimate the measurement uncertainty by sampling a pseudo-static signal without problem. The problem arises in the case, when the dynamic signal is sampled. How it follows from previous, not all of well-known producers publish all necessary parameters needed for the measurement uncertainty estimation by sampling the input signal with frequency near in order to the declared analogue bandwidth or to the Nyquist frequency referred to the maximum sampling rate. (It concerns already of the input signal with frequency about 10 - 30 times smaller than the maximum sampling frequency

² Some producers defines in data sheets the bandwidth of A/D module also as the frequency, by which the $THD < 1\%$ for the full scale input signal.

according our experience.) It fundamentally complicates the estimation of the measurement uncertainty for virtual instruments.

4. APPENDIX

Example 1. The measurement uncertainty estimation for the very low frequency signal sampling

If the temperature is within the specified range, the component u_{B1} (in V) is determined by the gain error, the offset error and the integral non-linearity. Using the 12 bits A/D module, the following parameters are published in data sheet for the set range ± 1 V ($FSR = 2$ V):

Gain error:	$\delta_G = 0.3 \%$
Offset error:	$\Delta_{Off} = 0.25$ mV
Integral non-linearity:	$INL = 0.2 \%$
Noise including quantisation:	$Noise = 0.8$ LSB

The expanded measurement uncertainty of one sample with value 0.3 V can be then determined (using the coverage factor $k = 2$) as follows:

$$\begin{aligned}
 U &= k u_c = 2 \sqrt{u_{B1}^2 + u_A^2} = \\
 &= 2 \sqrt{\left(\frac{\delta_G X / 100 + \Delta_{Off} + INL FSR / 100}{\sqrt{3}} \right)^2 + \left(\frac{Noise FSR}{(2^n - 1)} \right)^2} = \\
 &= 2 \sqrt{\left(\frac{0.003 \times 0.3 + 0.25 \times 10^{-3} + 0.002 \times 2}{\sqrt{3}} \right)^2 + \left(\frac{1.2 \times 2}{4095} \right)^2} = \\
 &= 2 \times 3.03 \times 10^{-6} \text{ V} = 6.1 \text{ mV}
 \end{aligned}$$

Example 2. The measurement uncertainty estimation for the dynamic signal sampling

If the temperature is within the specified range, the measurement uncertainty by the dynamic signal sampling is determined by the gain error, the offset error and $SINAD$. Using 16 bits A/D module, the following parameters are given in data sheets for the input range ± 5 V ($FSR = 10$ V):

Gain error:	$\delta_G = 0.05 \%$
Offset error:	$\Delta_{Off} = 1$ mV
Bandwidth:	320 kHz,
Signal to Noise and Distortion ratio:	$SINAD = 75$ dB

Sampling the input signal with the maximum frequency 100 kHz (only one channel is used), then the expanded measurement uncertainty of one sample with value 3 V can be estimated as follows (the coverage factor $k=2$):

$$\begin{aligned}
 U &= k u_c = \\
 &= 2 \sqrt{\left(\frac{\delta_G X / 100 + \Delta_{Off}}{\sqrt{3}} \right)^2 + \left(\frac{FSR}{2\sqrt{2}} 10^{-\frac{SINAD}{20}} \right)^2} = \\
 &= 2 \sqrt{\left(\frac{0.0005 \times 3 + 1 \times 10^{-3}}{\sqrt{3}} \right)^2 + \left(\frac{10}{2\sqrt{2}} 10^{-\frac{75}{20}} \right)^2} = \\
 &= 2 \times 1.1 \times 10^{-3} \text{ V} = 2.2 \text{ mV}
 \end{aligned}$$

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