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Uncertainty Issues in Multi-Channel Data Acquisition Systems

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Abstract—This paper deals with the analysis of multi-channel data-acquisition systems with the aim of identifying and combining the main uncertainty contributions. The approach based on the GUM uncertainty framework has been implemented to characterize and combine the different contributions. Particular attention has been paid towards cross-talk effects, which can be not negligible above all in multiplexed data-acquisition systems. The uncertainty analysis is described for a commercial data acquisition board, whose cross-talk specification is not suitable for a reliable uncertainty estimation in operating conditions. For this reason, an experimental characterization of the board has been performed and the obtained results are provided. These results highlight that a proper characterization of a data-acquisition system is effective in estimating the actual performance at the operating frequency and provide valuable information in terms of source resistance and input-channel configuration that make cross-talk effects negligible.

Index Terms—electrical quantities, data-acquisition systems, uncertainty, cross-talk

I. INTRODUCTION

The use of multi-channel data acquisition systems has been hugely increasing in the last decades for the measurement of both electrical and non-electrical quantities, thanks to their flexibility and scalability. These systems can be found in metrological laboratories as well as in industrial applications with very different uncertainty requirements. In [1] a multi-channel system for low-voltage signals in the bio-medical field is described, while [2] and [3] refer to applications for renewable energy sources. Structural-health monitoring [4] is another field where signals from several sensors are collected by a multi-channel data acquisition system. Other examples are in power metering [5], environmental monitoring [6] and for the characterization of energy harvesters [7]. Another key factor that has widened the use of such systems is the development of micro-controller based boards and embedded systems, which has pushed towards the arrangement of low-cost and very compact data acquisition systems [8]- [9].

As far as the uncertainty estimation is concerned, the identification and the propagation of the main contributions could be not a trivial task. Some problems in interpreting the manufacturer specifications from the user's point of view have been highlighted in [10] and an attempt in better stating these specifications have been proposed in [11], where the main uncertainty contributions for a single-channel system have been combined according to the GUM uncertainty framework [12]. A comparison between the GUM approach and the numerical Monte Carlo method [13] has been proposed in [14], where a single channel data-acquisition system has been analyzed for applications at very low frequency. Another single-channel application has been analyzed in [15], where the metrological characterization of virtual instrumentation has been performed and a numerical method has been proposed to simulate the Analogue-to-Digital conversion process. In multi-channel DAQ systems other problems arise that are mainly due to the cross-talk among channels and, in the case of multiplexed channels, to the settling time [8]- [9]. In addition, the presence of a multiplexer in the measuring chain requires particular attention in the estimation of the correlation between the measured quantities. Even though the standard IEEE 1057 [16] states the performance specifications that characterize a DAQ systems and provides methods for estimating related parameters, the interpretation of manufacturer specifications still remain questionable, above all when inter-channel effects have to be taken into account.

This paper deals with the uncertainty analysis of multi-channel data-acquisition systems with particular emphasis to the interaction between active channels. In the section II, a general description of the system is provided and the main uncertainty contributions are identified. In the section III, the GUM uncertainty framework is implemented and an example of uncertainty analysis is provided that refers to a commercial DAQ board. Experimental tests are also described that have been performed to estimate the cross-talk effects of the board.

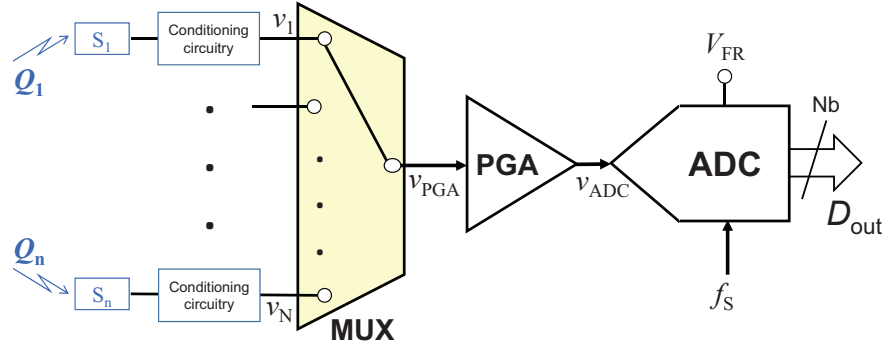


Fig. 1. Block scheme of a multi-channel data-acquisition system: low-cost solution based on the use of a multiplexer in the measuring chain.

Eventually, the final remarks are summarized in the section IV.

II. THE SYSTEM UNDER ANALYSIS

A. System description

A block scheme of a multi-channel data-acquisition system is shown in Fig. 1, where some of the components of the measuring chain are shared among different channels. This solution, which is based on the presence of a multiplexer (MUX), is very common in industrial applications, since it allows low-cost systems to be arranged.

The quantities under measurement Q_1, \dots, Q_n are converted into electrical quantities through a set of sensors (S_1, \dots, S_n) and pre-processed according to analogue conditioning circuitry. The voltage signals v_1, \dots, v_n are then routed to the input channels of a N-to-1 MUX, whose output is connected to a Programmable Gain Amplifier (PGA). The PGA is set to match as well as possible the amplitude of each voltage signal to the input range of the Analog to Digital Converter (ADC). The output code D_{out} of each channel is eventually processed according to the calibration function that describes each measuring channel, thus providing the measurements q_1, \dots, q_n of the input quantities. It is also possible that indirect methods are implemented in order to measure other quantities Y_1, \dots, Y_k that are related to a subset of the input quantities through suitable measurement models.

The presence of the MUX in the measuring chain has two important consequences in the uncertainty analysis:

- MUX-related contributions have to be identified and estimated;
- MUX-related effects have to be taken into account in the correlation analysis, since the systematic effects of PGA and ADC acts in the same extent on the different channels.

The most important uncertainty contribution due to the MUX is the cross-talk between channels. According to the scheme of Fig. 2, the parameter cross-talk CT for sinusoidal signals is defined in decibel (dB) as:

$$CT_{dB} = 20 \cdot \log_{10} \left(\frac{v_{1,2}}{v_2} \right) \quad (1)$$

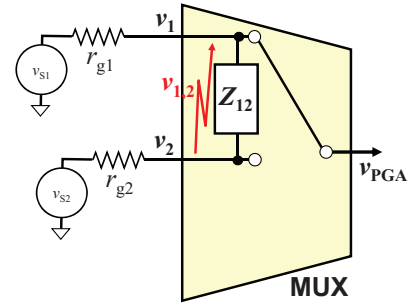


Fig. 2. The cross-talk effect in a multiplexed A/D system.

where $v_{1,2}$ is the root-mean square (rms) value of the disturbance that propagates to the channel 1 due to the rms-value v_2 of the signal on the channel 2.

The estimation of the cross-talk effect could be a tricky problem, since it depends on the non perfect insulation between the channels of the MUX and the possible ground loops among the active channels. An equivalent circuit that could allow the cross-talk to be estimated is shown in Fig. 2, where the impedance $Z_{1,2}$ represents the coupling between the MUX channels. However, the impedance $Z_{1,2}$ is usually not known and the figure also highlights that the cross-talk strongly depends on the source resistances r_{g1} and r_{g2} . Investigating the specifications of different commercial DAQ boards it arises that information provided by the manufacturer is often not enough to estimate cross-talk effects in operating conditions. For low-level DAQ boards, an estimation of this effect is not provided and manufacturers suggest to maintain the source resistance below a certain value to have negligible cross-talk contributions. For medium-high level boards, the cross-talk is stated for a specific frequency range, e.g. from DC (Direct Current) to 100 kHz, or at the upper bound of the frequency range. Unfortunately, most of the manufactures do not specify the source conditions and do not distinguish between adjacent and not adjacent channels.

Another problem related to the MUX is the transient due to the channel switching. In order to make this contribution negligible, manufacturers suggest to use low source resistance,

e.g. below 1 k Ω . Furthermore, a suitable settling-time has to be set in order to allow the transient to be extinguished before the ADC samples the signal v_{ADC} . This setting is a trade-off between uncertainty and sampling rate, since the actual sampling frequency of each channel mainly depends on the settling time value. As an example, in a four channel multiplexed system with a settling time of 2 μs , the sampling frequency of each channel will be 125 kSa/s, i.e. $1/(4 \cdot 2 \mu\text{s})$, even though the ADC can work at a rate higher than 500 kSa/s. In the analysis proposed in this paper, the assumption of settling time that minimizes the contribution of the transient is always considered valid.

B. Uncertainty analysis

The Input/Output (I/O) relationship that refers to each of the active channels is obtained starting from the code $D_{\text{out},i}$ at the output of the ADC, which can be expressed as:

$$D_{\text{out},i} = \frac{v_{\text{ADC},i}}{V_{\text{q}}} = \frac{G_i \cdot v_{\text{PGA}}}{V_{\text{FR}}/2^{N_b}} \quad (2)$$

where G_i is the gain of the PGA when the i -th channel is selected, while V_{FR} and N_b are full-range voltage and number of bit of the ADC, respectively.

If the previous expression is rewritten highlighting the main uncertainty contributions, the output code D_{out} that corresponds to the input channel 1 becomes:

$$D_{\text{out},1} = \frac{G_1 \cdot 2^{N_b} \cdot (v_1 + v_1^{\text{CT}} + V_{\text{off,RTI}})}{V_{\text{FR}}} + D_{\text{off}} + \delta_{\text{q}} \quad (3)$$

where v_1^{CT} is the error term related to the cross-talk, $V_{\text{off,RTI}}$ is the offset voltage Referred To Input of the PGA, D_{off} is the offset error of the ADC, while δ_{q} is the ADC quantization error.

Starting from equation (3), the voltage v_1 can be estimated as:

$$v_1 = \frac{V_{\text{q}} \cdot D_{\text{out},1}}{G_1} \cdot (1 + \epsilon_{\text{G}}) - \left(\frac{V_{\text{q}} \cdot D_{\text{off}}}{G_1} + V_{\text{off,RTI}} \right) + \frac{V_{\text{q}} \cdot \delta_{\text{q}}}{G_1} - v_1^{\text{CT}} + e_{\text{LE}} + e_{\text{CMRR}} + n \quad (4)$$

where ϵ_{G} is the term that takes into account the relative error of PGA and ADC reference-voltage and also includes the non linearity of the system, n represents the effect of the electronic noise, while the other two terms e_{LE} and e_{CMRR} represents the systematic effects due to the load effect and the Common-Mode Rejection Ratio (CMRR) of the PGA.

In the equation (4), the uncertainty contributions of the single components that made up the measuring chain of Fig. 1 are highlighted, with the exception of sensors and conditioning circuitry. If the input/output relationship $v_1 = f(Q_1)$ of sensor and conditioning circuitry is known, the input quantity Q_1 can be estimated from the calibration function $Q_1 = f^{-1}(v_1)$, including the uncertainty contributions related to this calibration function. With the aim of developing guide-lines that can be used as general rules for the uncertainty estimation

in multiplexed A/D systems, hereafter the analysis will be focused on the estimation of the voltage signals at the input channels of the mutiplexer.

Equation (4) can be used for estimating the uncertainty of the voltage signal v_1 if the different contributions have been estimated. However, if the acquisition system of Fig. 1 is integrated inside a micro-controller chip or represents the common architecture of a DAQ Board, the characterization results of the whole measuring chain are available. In this situation, the equation (4) can be rewritten as:

$$v_1 = \frac{V_{\text{q}} \cdot D_{\text{out},1}}{G_1} \cdot (1 + \epsilon_{\text{G}}) + e_{\text{OFF}} + e_{\text{q}} + v_1^{\text{CT}} + e_{\text{LE}} + e_{\text{CMRR}} + n \quad (5)$$

where

$$e_{\text{OFF}} = \frac{V_{\text{q}} \cdot D_{\text{off}}}{G_1} + V_{\text{off,RTI}} \quad (6)$$

$$e_{\text{q}} = \frac{V_{\text{q}} \cdot \delta_{\text{q}}}{G_1}$$

The application of the GUM uncertainty framework for the uncertainty estimation requires that each error term that is present in the equation (5) is considered as a random variable (r.v.) after the main systematic effects have been corrected. For the terms ϵ_{G} and e_{OFF} , the assumption of r.v. with expected values equal to zero and standard uncertainties $u(\epsilon_{\text{G}})$ and $u(e_{\text{OFF}})$, respectively, is considered. The term e_{q} can be also considered a r.v. with zero expected value and standard uncertainty $u(e_{\text{q}}) = e_{\text{q}}/\sqrt{12}$, but only if the sampling process is uncorrelated with respect to the input signal or the internal noise is larger than the quantization noise.

The systematic effect e_{LE} depends on the source impedance and on the impedance Z_{IN} of the input channel, which is usually represented by means of a resistance R_{IN} shunted by a capacitance C_{IN} . Since R_{IN} is of the order of gigaohm and C_{IN} could be tens of picofarad, the load effect is negligible at low frequencies for source resistance up to few kilohm, while it could be comparable to the other uncertainty contributions at high frequencies. The term e_{CMRR} is instead related to the parameter CMRR of the PGA and to the Common-Mode voltage v_{CM} , which is the average of the voltages applied to the two inputs of the PGA. It could become comparable to the other uncertainty contributions if a small differential voltage is measured with a high common-mode voltage. When these two systematic effects are not negligible, their compensation has to be implemented in the calibration function and the residual uncertainty contribution has to be estimated.

The characteristics of the term v_1^{CT} depend on the possible correlation between the signal v_1 (the quantity under measurement) and the signal v_2 , which is responsible for the disturbance that propagates to the adjacent channel. One should note that if a real-time uncertainty estimation is not required, a post-processing analysis can be implemented to estimate the correlation between the signals v_1 and v_2 , thus better characterizing the r.v. v_1^{CT} . Furthermore, if the equivalent electrical circuit of the cross-talk effect is available,

e.g. as that of Fig. 2, the cross-talk contribution could be considered as a systematic effect. In the next section, a numerical example is provided that allows the uncertainty contributions due the cross-talk to be compared to the other contributions. Experimental results are also described that refer to the characterization of a commercial DAQ Board.

III. EXAMPLE OF UNCERTAINTY ESTIMATION

If the quantities to be estimated are the voltage signals at the input of the MUX, the calibration function of each channel is expressed by the equation (5). A numerical example is here provided referring to a commercial DAQ Board with the following specifications:

- bipolar full-range from -5 V to $+5$ V; $N_b = 16$
- maximum sample rate: 250 kSa/s
- $\epsilon_G = 85 \cdot 10^{-6}$; $e_{\text{OFF}} = 0.2$ mV; $u(n) = 118$ μ V
- $R_{\text{IN}} > 10$ G Ω ; $C_{\text{IN}} = 100$ pF
- $CMRR = 100$ dB (DC to 60 Hz)
- $CT = -75$ dB @ 100 kHz (adjacent channels)
- $CT = -90$ dB @ 100 kHz (non-adjacent channels)

According to the voltage full-range and the number of bit, the quantization uncertainty is estimated as $u(e_q) \approx 44$ μ V, which combined to the noise contribution provides $u(e_q+n) \approx 126$ μ V for single readings.

Information related to the probability distribution of gain and offset errors is rarely available, then a conservative choice is made considering these r.v. characterized by uniform probability density functions (pdf) with zero expected values and upper bounds equal to ϵ_G and e_{OFF} , respectively. The corresponding standard uncertainties can be then estimated as:

$$u(\epsilon_G) = \frac{2 \cdot \epsilon_G}{\sqrt{12}} \approx 49 \cdot 10^{-6}; u(e_{\text{OFF}}) = \frac{2 \cdot e_{\text{OFF}}}{\sqrt{12}} \approx 115 \mu\text{V} \quad (7)$$

About the systematic effect related to the load of the DAQ Board, starting from the stated input impedance, an upper frequency limit can be estimated that makes negligible the term e_{LE} , i.e. lower than $\epsilon_G/4 \approx 20 \cdot 10^{-6}$. In order to maintain the relative load effect within this limit, the maximum frequency of the input signal is about 100 kHz for a source resistance up to 100 Ω and 10 kHz for a source resistance up to 1 k Ω . The effect of the error term e_{CMRR} can be neglected (relative effect lower than $20 \cdot 10^{-6}$) for common-mode voltages v_{CM} up to the double of the differential voltage v_{D} , since $CMRR = 100$ dB. One should note that this condition is met when voltage signals referred to ground are measured, since in this condition $v_{\text{CM}} \approx v_{\text{D}}/2$.

Combining all the uncertainty contributions, with the exception of the term related to the cross-talk, and considering them uncorrelated, i.e. $\rho(x_i, x_j) = 0$, the standard uncertainty of the voltage measurement v_1 is obtained as:

$$u(v_1) = \sqrt{v_1^2 \cdot u^2(\epsilon_G) + u^2(e_{\text{OFF}}) + u^2(e_q + n)} \quad (8)$$

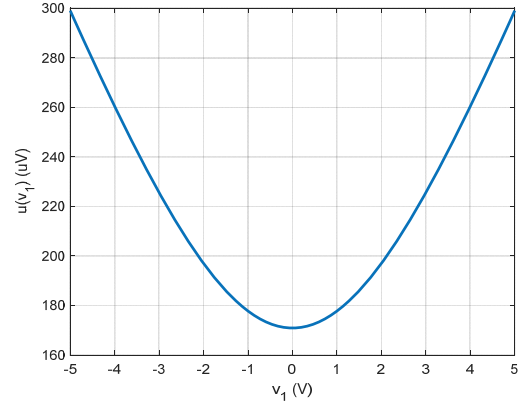


Fig. 3. The standard uncertainty of the measured voltage v_1 without considering the cross-talk contribution.

The behavior of $u(v_1)$ within the range from -5 V to $+5$ V is shown in the Fig. 3 with values that are included in the range $(171 \div 300)$ μ V.

The next step is the estimation of the uncertainty contribution related to the cross-talk of the MUX, but the specifications provided by the manufacturers often not allow a reliable estimation of this contribution to be obtained. As in this example, the parameter CT is stated at a specific frequency (100 kHz) and the conditions for the source resistances of the involved channels are not well specified. Furthermore, the definition of cross-talk given in the equation (1) refers to sinusoidal signals at the input of the MUX. These reasons make questionable the estimation of the cross-talk contribution for arbitrary signals that are characterized by components at very low frequency. The impedance $Z_{1,2}$ in Fig. 2 has both a real and an imaginary component [17], but the limited available information prevents any reliable estimation of these components, which can be obtained only implementing a specific experimental procedure, as described in the next section.

A. Cross-talk characterization

The DAQ Board used here as a test case has been subjected to an experimental characterization, with the aim of estimating the cross-talk effects in different conditions and for different signal frequencies. A block scheme of the set-up that has been arranged to perform this characterization is shown in Fig. 4.

A signal generator (Tektronix model AFG-3252), which is connected to the PC through a USB interface and controlled by a LabView Virtual Instrument (VI), is configured to apply sinusoidal voltage signals at the input channel 2 of the DAQ Board through the source resistance r_{g2} . The same VI acquires samples from the input channel 1 of the DAQ Board, which is grounded by means of the resistance r_{g1} . The VI sets amplitude and frequency of the input signal v_2 and then acquires 125 kSamples per channel (sample rate 125 kSa/s) for each test frequency. The set of samples collected at each frequency are processed according to a Fast Fourier Transform (FFT) algorithm, which provides an estimation of the amplitude $v_{1,2}$

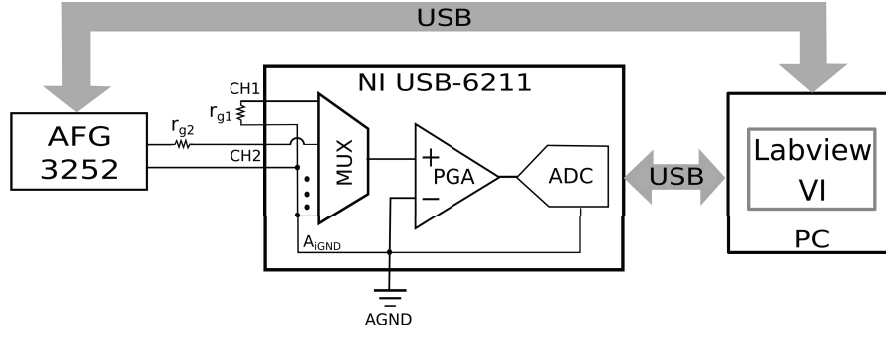


Fig. 4. Block scheme of the experimental set-up that has been arranged to estimate the cross-talk effects.

of the signal on the channel 1 corresponding to the amplitude v_2 of the signal on the channel 2. Eventually, the parameter CT_{dB} is estimated according to equation (1).

A first series of tests has been performed with the input channels of the DAQ Board in Referenced Single Ended (RSE) configuration and the channel 1 connected to ground through three different values of the resistance r_{g1} ($\approx 0 \Omega$, $1 \text{ k}\Omega$ and $10 \text{ k}\Omega$), while the source resistance r_{g2} has been maintained at 50Ω . The estimated CT values between adjacent channels, which are shown in the Fig. 5 for frequency in the range from 1 Hz to 62 kHz , highlight the large sensitivity of the cross-talk uncertainty contribution with respect to the source resistance, with changes from -98 dB ($r_{g1} \approx 0 \Omega$, continuous blue line) to about -52 dB @ 1 Hz ($r_{g1} = 10 \text{ k}\Omega$, dotted black line) and from -74 dB ($r_{g1} \approx 0 \Omega$) to about -40 dB @ 62 kHz ($r_{g1} = 10 \text{ k}\Omega$). For the tested board, the obtained figures highlight that the source resistance has to be maintained as small as possible, as also suggested in [17].

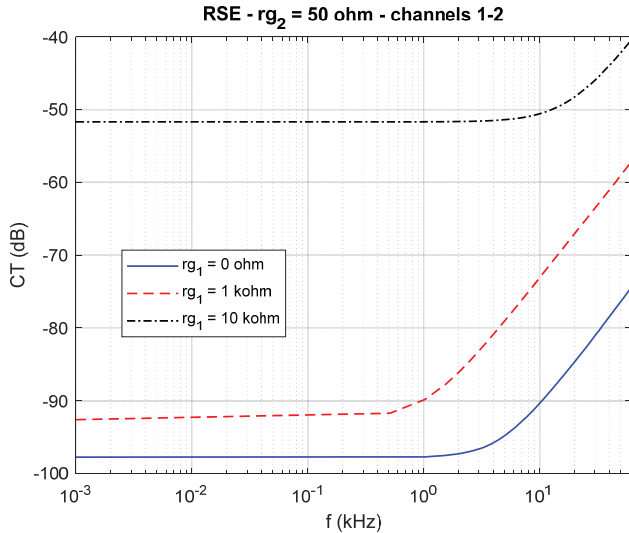


Fig. 5. The estimated cross-talk between adjacent channels for three different source resistances of the channel 1.

Another series of tests here presented has been performed with the aim of investigating how the parameter CT is

different if non-adjacent channels are scanned by the MUX. The source resistances r_{g1} and r_{g2} have been fixed to $1 \text{ k}\Omega$ and 50Ω , respectively, while the signal v_2 (the responsible for the disturbance) has been connected to the channel 2, 3 and 8 during three different experimental sessions. The obtained results are summarized in the Fig. 6 and show negligible differences (lower than 1 dB) for frequencies lower than 500 Hz , while the parameter CT has an improvement of about 20 dB (from -60 dB to -80 dB) and of about 28 dB (from -60 dB to -88 dB) @ 62 kHz if the interference between the non-adjacent channels 1-3 and 1-8 is considered. This result suggests to connect input signals to non-adjacent channels if enough unused spares are available and to ground the unused channels to minimize the cross-talk effects.

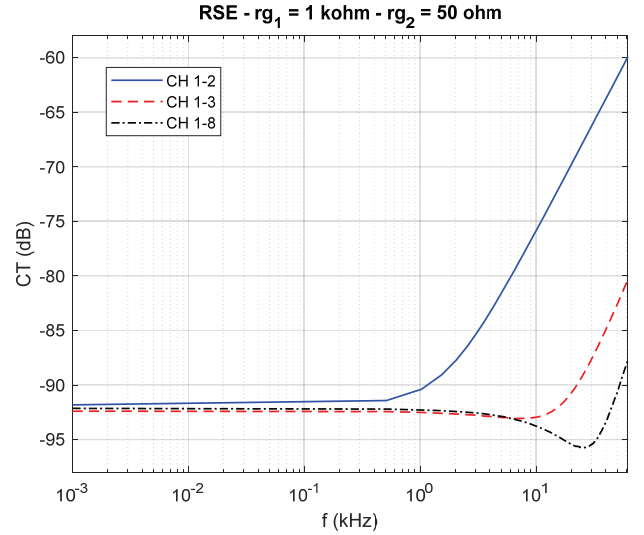


Fig. 6. The estimated cross-talk between adjacent channels and non-adjacent channels.

B. Cross-talk uncertainty contribution

The experimental results presented in the previous section suggest the possibility to identify a suitable model that describes the transfer function between adjacent and non-adjacent channels, thus obtaining a reliable estimation of the

uncertainty contribution that is related to the cross-talk. The identification of the impedance $Z_{1,2}$ requires the measurements of the amplitude of the signal $v_{1,2}$ as well as of its phase with respect to the signal v_2 . The authors are now working on this characterization. However, with the available results it is possible to obtain a preliminary estimation of the cross-talk effect.

In the conditions of the Fig. 6, i.e. $r_{g1} = 1 \text{ k}\Omega$ and $r_{g2} = 50 \text{ }\Omega$, the cross-talk is lower than -90 dB up to 1 kHz for adjacent channels as well as for non adjacent channels. Using this cross-talk value, the term v_1^{CT} of equation (5) has been estimated in the range from $-32 \text{ }\mu\text{V}$ to $+32 \text{ }\mu\text{V}$ for all the possible combinations between the voltages of the signals v_1 and v_2 . If the two signals are independent and characterized by a uniform pdf in the range from -5 V to $+5 \text{ V}$, the r.v. v_1^{CT} can be characterized by a triangular pdf with zero expected value and maximum value equals to $32 \text{ }\mu\text{V}$, then the standard uncertainty related to the cross-talk is estimated as:

$$u(v_1^{\text{CT}}) = \frac{2 \cdot 32 \text{ }\mu\text{V}}{\sqrt{24}} \approx 13 \text{ }\mu\text{V} \quad (9)$$

that is negligible with respect to the uncertainty due to the other contributions (see Fig. 3).

In the presence of higher source resistance r_{g1} , the situation can be very different. If $r_{g1} = 10 \text{ k}\Omega$ (see Fig. 5), in the same frequency range the cross-talk reaches the value -52 dB , which corresponds to a standard uncertainty of about 10 mV . Attention has also to be paid when signals at higher frequency are acquired. With $r_{g1} = 1 \text{ k}\Omega$ and $r_{g2} = 50 \text{ }\Omega$, at 10 kHz the cross-talk remains a negligible contribution if the MUX scans non adjacent channels, but in the case of adjacent channels, the cross-talk reaches about -75 dB and the corresponding standard uncertainty is equal to about 0.7 mV .

IV. CONCLUSIONS

The GUM uncertainty framework has been implemented in this paper for the uncertainty estimation of measurements provided by a multi-channel data acquisition system. In particular, a multiplexed A/D system has been investigated, since this is the architecture that is often employed to arrange low-cost systems. The different uncertainty contributions have been taken into account, with particular attention to the contribution that arises when a MUX is present in the measuring chain, which is the one related to the cross-talk. Unfortunately, the manufacturer specifications do not provide enough information to obtain a reliable estimation of this contribution in operating conditions. For this reason, an experimental procedure has been implemented to estimate the cross-talk effect at different frequencies and for different source resistance of the active channel. Preliminary results have been provided that refer to a commercial DAQ Board in RSE configuration for the input channels. These results have shown that the DAQ-board characterization is effective in estimating the actual contribution of the cross-talk at the operating frequency. In addition, very useful information can be obtained that are related to the configuration of the measurement circuit (source

resistance and active channels) that minimize the cross-talk contribution. A proper characterization of the cross-talk effects is then advisable in order to obtain a reliable estimation of the measurement uncertainty in operating conditions.

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