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CALIBRATION OF PXI DATA ACQUISITION CARDS USED FOR PRIMARY IMPEDANCE METROLOGY

Calibration procedure and requirements for self- and external calibration of National Instrument (NI) PXI data acquisition cards is presented in the paper. Calibration results of the PXI-446X cards used at Department of Measurement Science, Electronics and Control (KMEiA) of Silesian University of Technology are presented. The results show that calibration procedure was successful and the metrological parameters of the PXI-446X devices used at KMEiA was improved. Measurement results obtained after adjustment differ from the reference values of the DC voltage calibrator used for the calibration purpose by no more than 0.7 mV.

KALIBRACJA KART AKWIZYCJI DANYCH PXI WYKORZYSTYWANYCH W METROLOGII IMPEDANCYJNEJ WYSOKICH DOKŁADNOŚCI

W artykule przedstawiono procedury autokalibracji i procedury kalibracji zewnętrznej kart akwizycji danych PXI produkcji National Instruments. Zamieszczono wyniki kalibracji kart serii PXI-446X wykorzystywanych w Katedrze Metrologii, Elektroniki i Automatyki (KMEiA) Politechniki Śląskiej. Efektem kalibracji jest znaczna poprawa parametrów metrologicznych urządzeń. Wyniki pomiarów napięć otrzymane po adiustacji różnią się od wartości wzorcowych na wyjściu kalibratora nie więcej niż 0.7 mV.

1. INTRODUCTION

The National Instrument (NI) PCI eXtensions for Instrumentation (PXI) modular system is one of several modular electronic instrumentation platforms in current use. The platform is used as a basis for building electronic test equipment, automation systems and modular laboratory instruments. Flexibility and possibility to trigger and synchronize multiple devices led to a multitude of applications of the PXI devices in industry and science. Moreover, due to very good functional and metrological parameters, like time stability, high resolution of analog-to-digital and digital-to-analog converters (ADCs and DACs), low noise and distortion, stability as well as high resolution of adjustment of their frequency, the PXI devices began to be used at National Metrology Institutes (NMIs), Designated Institutes (DIs) and many other calibration laboratories to build systems for comparison of impedance standards [1]-[3].

In recent years, fully-digital ratio impedance bridges [4]-[8] have emerged as device suitable for primary impedance metrology. In a sampling (or digitizing) bridge [5]-[8], usually consisting of a two-phase digital signal source and a sampling system synchronized with the source, an impedance ratio is compared to a ratio determined from series of samples obtained from digitizing voltage signals. Research conducted by several European NMIs (e.g. METAS from Switzerland and Trescal from Denmark) and some research institutes (like University of Zielona Góra, UZG) confirmed the usefulness of the PXI devices for precise voltage ratio measurements in impedance comparison systems [9]-[11].

For few years research team from Silesian University of Technology (SUT) has been participating in international work concerning development of versatile electrical impedance calibration laboratory based on digital impedance bridges [12]. Therefore, SUT has developed an PXI modular system based on PXI-1036 chassis. The system, together with extremely stable two-channel source of digitally synthesized AC voltage [13, 14], enables impedance comparison in the frequency range from 10 Hz to 20 kHz with relative accuracy up to 10^{-6}.

2. PXI SYSTEM USED AT SUT

Department of Measurement Science, Electronics and Control (in Polish: Katedra Metrologii, Elektroniki i Automatyki, KMEiA) of SUT is equipped with National Instrument PXI system (see Fig. 1, indication “1”) having:
- high-performance modular data acquisition card PXI-4462 with four 24-bits sigma-delta ADCs featuring maximum sampling rate equal to 204.8 kS/S. An optically coupled trigger signal can be used to start the measurement synchronously with an external signal;
- high-performance modular data acquisition card PXI-4461 with two 24-bits sigma-delta ADCs featuring maximum sampling rate of 204.8 kS/S. As well as

in case of PXI-4462 card an optically coupled trigger signal can be used to start the measurement synchronously with an external signal;
- a timing and synchronization module (NI PXI-6653) which allows replacing the native 10 MHz signal distributed over the backplane of the PXI chassis by very stable and accurate frequency source generated by an ovenized quartz crystal oscillator (OCXO). Moreover, the OCXO can be phase locked to any external frequency signal being a multiple of 1 MHz reference signal;
- 64-channel external relay driver module (NI PXI-2567). It supplies signals driving relay coils which can be synchronized with signals generated by other PXI module.

The above mentioned devices are placed in PXI-1036 chassis (see Fig. 1) accompanied with a high-performance source of digitally synthesized sinusoidal voltage, a bespoke multiplexer and PC with LabVIEW enable realization of digitizing impedance bridge [15].

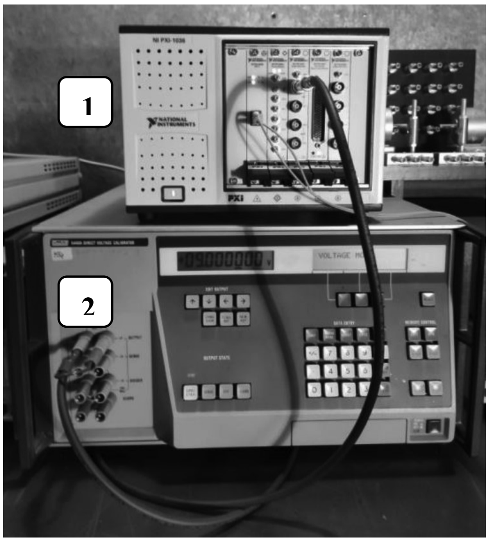


Fig.1. View of the measurement setup: 1 – DC voltage calibrator Fluke 5440, 2 – PXI system with the PXI-6653 (slot 2), PXI-4461 (slot 3), PXI-2567 (slot 4) and the PXI-4462 (slot 5)
Rys. 1. Stanowisko do kalibracji: 1 – kalibrator napięcia stałego Fluke 5440, 2 – PXI system z PXI-6653 (slot 2), PXI-4461 (slot 3), PXI-2567 (slot 4) i PXI-4462 (slot 5)

3. CALIBRATION OF THE PXI-6653 DEVICES

In general, calibration of an instrument consists of verifying its the measurement accuracy and correcting for detected measurement error. NI

modular data acquisition cards should be externally calibrated at a regular interval as defined by the measurement accuracy requirements of an application. The NI PXI-6653 is factory calibrated at 25°C to the levels indicated in specifications [16]. The associated calibration constants – the corrections that were needed to meet specifications – are stored in the onboard nonvolatile memory. The driver software uses these stored values. The factory calibration of the PXI-6653 involves calculation and storing of four calibration constants. These values control the accuracy of four features of the device:
1) OCXO (oven-controlled crystal oscillator) frequency – the OCXO frequency can be adjusted over a small range. The output frequency of the OCXO is adjusted using this constant to meet the specification listed in [16];
2) PXI_CLK10 phase – when using the phase lock loop to lock PXI_CLK10 signal to an external reference clock, the time delay between rising edges the clock pulses can be adjusted. Thanks to this feature the time between rising edges of PXI_CLK10 and the input clock can be reduced.
3) Direct Digital Synthesizer (DDS) start trigger phase – to start the direct digital synthesizer reliably, the DDS start trigger must arrive within a certain window of time. The phase of the DDS start trigger is controlled by this constant to meet the setup and hold-time requirements of the DDS;
4) DDS initial phase – the phase of the DDS output is adjusted using this constant so that the signals generated by DDS circuits of multiple synchronized PXI-6653 modules can be phase- or time aligned.

Self-calibration of the PXI-6653 module is impossible. Only National Instruments calibration center is able to calibrate it. The NI PXI-6653 used at SUT is quite new and first external calibration at NI calibration center is scheduled for 2021.

4. CALIBRATION OF THE PXI-446X DEVICES

NI-4461 and NI-4462 cards (hereinafter marked 446X) support two types of calibration: self-calibration and external calibration. Self-calibration, also known as internal calibration, uses a software command and requires no external connections nor equipment. During the self-calibration the calibration constants are adjusted to account for any errors caused by short-term fluctuations in the operating environment. Self-calibration improves measurement accuracy by compensating for variables such as temperature that might have changed since the last external calibration. Self-calibration retains the traceability of the external calibration. External calibration should be generally performed using high-precision traceable instruments at either NI calibration center or a metrology lab. This procedure replaces all calibration constants in the onboard non-volatile calibration memory (EEPROM) and is equivalent to a factory calibration at NI calibration center. Because the external calibration procedure changes all constants stored in EEPROM, it invalidates the original calibration certificate. If an external calibration is done with traceable instruments, a new calibration certificate should be issued.

National Instruments recommends performing a complete calibration at least once every year. Self-calibration can be performed as needed or when ambient temperature differs by 5°C or more from ambient temperature of the last external calibration. It needs to be highlighted that precision of the NI-446X cards is of utmost importance for accurate voltage ratio measurements. Accuracy of the voltage measurement is directly related to the accuracy of the impedance ratio measurement. Hence, based on our measurement accuracy needs, we assumed six (not twelve) months interval for external calibration of the PXI-446X. Moreover, self-calibration is performed at SUT always as the first step of each program execution by writing proper instruction in LabVIEW software.

4.1. Test equipment and conditions

Laboratory of Precise Electrical Measurements of KMEiA is equipped with calibrators and multimeters capable of calibrating PXI-446X cards. Taking into account recommendation of the NI, a high accurate DC voltage source is necessary to calibrate analog inputs of the PX-446X. Therefore, a Fluke 5440A (F5440A) direct voltage calibrator was used. The instrument, according to its specification, has output uncertainty $u = \pm$ (3.5 μV/V of output + 5 μV) on its 11 V range. The F5440A output was connected to PXI-446X inputs with a short cable. In order to confirm accuracy of the instrument the input voltage of PXI-446X was measured with high-performance 8½ digit Keysight 3458A (K3458A) multimeter which has calibration certificate traceable to German national standard of DC voltage. All instruments were warmed-up by the time specified in their respective manuals [17]. Measurements were made in electromagnetically shielded and air-conditioned room (25°C) for each input signal range of the PXI-4461 (ai0 and ai1) and the PXI-4462 (ai0 to ai3). Ranges and gain accuracy limits taken from PXI-446X documentation [17] are presented in Table 1.

Table 1

Analog input ranges and gain accuracy limits for the PXI-446X

PXI-446X nominal gain	**Full-Scale range**	**Calibrator output voltage**	**Accuracy limit**
dB	**V**	**V**	**V**
-20	±42.4	9.0	±0.0311
-10	±31.6	9.0	±0.0311
0	±10.0	9.0	±0.0311
10	±3.16	3.0	±0.0104
20	±1.0	0.9	±0.0031
30	±0.316	0.3	±0.0010

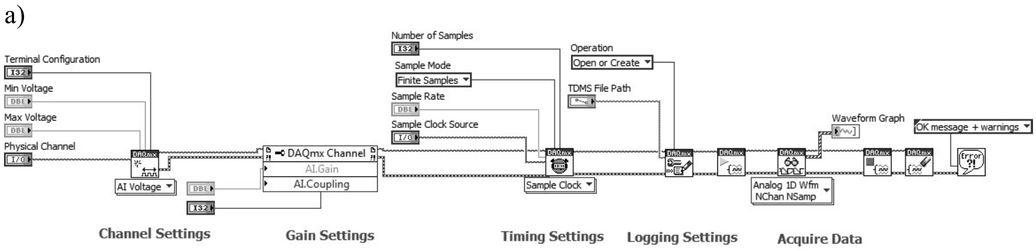
4.2. Procedure and results

The external calibration process of the PXI-446X consists of the following steps:

1) verification procedure – to verify the accuracy of the device prior to calibration;
2) adjustment procedure – to adjust the device calibration constants with respect to known voltage generated by the external DC voltage source (e.g. a DC voltage calibrator);
3) re-verification procedure – to ensure that the device operates within the specification limits after adjustment.

Verification procedure prior to calibration was performed using the system presented in Fig.1. A block diagram and front panel of the virtual instrument written in LabVIEW to acquire verification results is presented in Fig. 2a. One hundred thousand samples with 200 kS/s rate were taken into consideration. Hence total acquisition time equals 0.5 s (see Fig. 2b). Measurement conditions described in section 4.1 were observed. Verification results are presented in Table 2, where average voltages (in volts) and standard deviations of average (in grey-shaded cells, in μV) are shown. It is clearly visible that all verification results are within accuracy limits given in Table 1. However, the average values are a slightly shifted from the calibrator output voltages given in Table 1. Therefore, it was decided to improve the PXI-446X accuracy and adjust the parameters of its processing channels corresponding to both analog inputs. In order to perform adjustment in accordance with manufacturer procedure [18], the output of the F5440A calibrator was connected to all the analog input channels of the 446X devices using coaxial cables.

a)



b)

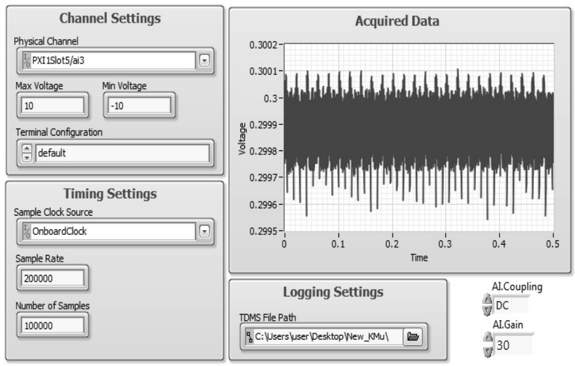


Fig.2. Virtual instrument (VI) written in LabVIEW for verification of PXI-446X device: a – block diagram of the VI, b – front panel of the VI. Results obtained for channel ai3 of PXI-4462 are visible on the graph

Rys. 2. Przyrząd wirtualny (VI) utworzony w środowisku LabVIEW w celu weryfikacji urządzeń PXI-446X, a – diagram blokowy, b – płyta czołowa. Na wykresie widoczne są dane otrzymane podczas badania kanału ai3 modułu PXI-4462

Table 2

Analog input verification results of the ai0 - ai1 channels of the PXI-4461 and ai0 - ai3 channels of the PXI-4462

Range \ Channel	4461 AI0	4461 AI1	4462 AI0	4462 AI1	4462 AI2	4462 AI3
-20 dB	8.9992	8.9991	8.9990	8.9981	8.9976	8.9986
	1.02	1.02	1;01	1.02	1.02	1.01
-10 dB	8.9987	8.9989	8.9982	8.9978	8.9978	8.9983
	0.75	0.75	0.75	0.74	0.75	0.75
0 dB	8.9980	8.9977	8.9967	8.9965	8.9961	8.9963
	0.43	0.43	0.42	0.42	0.43	0.43
10 dB	2.9987	2.9989	2.9986	2.9985	2.9985	2.9986
	0.39	0.40	0.40	0.39	0.40	0.40
20 dB	0.8996	0.8997	0.8996	0.8996	0.8996	0.8996
	0.37	0.37	0.37	0.37	0.37	0.37
30 dB	0.2998	0.2999	0.2998	0.2998	0.2998	0.2998
	0.41	0.40	0.40	0.40	0.41	0.40

The voltage was set to 5 VDC and adjustment was initialized using LabVIEW program shown in Fig. 3. As shown in picture, the external calibration is protected by password “NI/0” to prevent accidental changes to the device parameters.

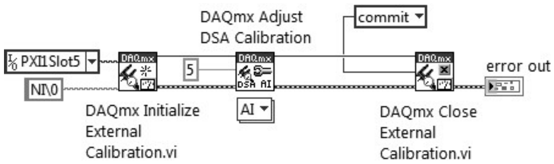


Fig. 3. Virtual instrument in LabVIEW used for adjustment of the PXI-4462 device (Slot 5)
Rys. 3. Przyrząd wirtualny w LabVIEW utworzony w celu adiustacji urządzenia PXI-4462 (Slot 5)

At the end of the adjustment procedure, the new constants are stored in the external calibration area of the PXI-446X non-volatile calibration memory what ensures that these constants will not be accidentally modified during a self-calibration procedure.

The last step of the external calibration process was a re-verification procedure. To verify results obtained after adjustment procedure all measurements performed before adjustment were repeated. The system presented in Fig.1 was used for this purpose and the measurement conditions described in Section 4.1 were kept. Results (in volts) are presented in Table 3. Standard deviation of

Table 3

Analog input re-verification results of the ai0 - ai1 channels of the PXI-4461and ai0 - ai3 channels of the PXI-4462

Channel / Range	4461 AI0	4461 AI1	4462 AI0	4462 AI1	4462 AI2	4462 AI3
-20 dB	9.0005	9.0002	9.0002	9.0005	9.0000	9.0002
	1.00	1.01	1.02	1.01	1.02	1.02
-10 dB	9.0006	9.0001	9.0002	9.0003	9.0001	9.0002
	0.73	0.75	0.74	0.72	0.74	0.74
0 dB	8.9992	8.9993	8.9992	8.9993	8.9991	8.9994
	0.44	0.41	0.44	0.43	0.42	0.42
10 dB	2.9993	2.9995	2.9994	2.9995	2.9996	2.9996
	0.39	0.39	0.40	0.40	0.39	0.40
20 dB	0.8999	0.8999	0.9000	0.9000	0.9000	0.9000
	0.37	0.37	0.36	0.37	0.37	0.36
30 dB	0.3000	0.3000	0.3000	0.3000	0.3000	0.3000
	0.40	0.40	0.41	0.40	0.40	0.41

average are presented in grey cells (in μV). It is clearly visible that the voltage values after adjustment have significantly lower bias than before adjustment. Standard deviations at the same level as previously are observed.

5. CONCLUSION

Re-verification results show that calibration procedure was successful and the metrological parameters of the PXI-446X devices used at KMEiA was improved. Measurement results obtained after adjustment are within accuracy limits given by the manufacturer. Moreover, average values differ from the reference values at the calibrator output not more than 0.7 mV. When a single PXI-446X digitizer is used to measure the complex voltage ratio then its inaccuracy does not critically affect the accuracy of such measurement. In the case of a sampling impedance bridge it is the digitizer nonlinearity error, not the gain error, which determines the accuracy of the bridge. However, the KMEiA also considers using two digitizers to measure the complex voltage ratio. In this case, a significant difference in the gain errors of both digitizers can have a negative impact on the accuracy of complex voltage ratio measurement.

It it planned to perform complete calibration and adjustment procedure of PXI-446X devices at KMEiA once every year using high-precision DC calibrator traceable to the national (Polish or other country) primary standard. Such an approach is consistent with the recommendations of National Instruments. If significant drifts are observed, the reduction of the calibration interval will be considered. It should be noted that in our work we focused only on calibration of channels corresponding to analog inputs, because only they are used in the digital impedance bridge we are developing at SUT. However, in other applications an appropriate calibration of PXI-446X analog outputs and timebase frequency can be necessary.

The digital impedance bridge with calibrated NI PXI-446X data acquisition cards is currently being extensively tested at KMEiA. Programs in LabVIEW software are being developed to enable full automation of balancing the bridge and compare the impedance standards.

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