euspen's 20th International Conference & Exhibition, Geneva, CH, June 2020

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Performance evaluation of low-cost vibration sensors in precision manufacturing applications

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Abstract

The recent development of low-cost accelerometers, driven by the Industrial Internet of Things (IIoT) revolution, provides an opportunity for their application in precision manufacturing. Sensor data is oft of highest consideration in any precision machining process. While traditionally high cost vibration sensors have been employed for vibration measurements in industrial manufacturing scenarios, the aspects related to the measurement uncertainty affecting the accuracy of low-cost vibration sensors have not been explored and requires performance evaluation. This research focuses on the characterization of measurements from low cost tri-axial accelerometers in terms of identifying the parameters that induce uncertainties in measured data.

Static and dynamic calibration was conducted on a calibration test bench using a range of frequencies while establishing traceability according to the ISO 16063 and the IEEE-STD-1293-2018 standards. Moreover, comparison tests were performed by installing the sensors on machine tools for reliability evaluation in terms of digital transmission of recorded data. Both tests would further establish the relationship between the base line errors originating from the sensors and their influence on the data obtained during the dynamic performance profile of the machine tools. The outcomes of this research will foresee the viability offered by such low-cost sensors in metrological applications enabling Industry 4.0.

Keywords: Precision Manufacturing, Measuring Instruments, Performance Evaluation, Uncertainty, Accelerometers, Calibration

1. Introduction

Vibration monitoring is one of the key areas of interest in precision manufacturing setups [1] to ensure high level of engineering confidence in manufactured products [2]. Traditionally, high accuracy vibration sensors, such as Integrated Electronics Piezo-Electric (IEPE) accelerometers, have been employed in industrial manufacturing scenarios [1]. However recent growth of accelerometers based on Micro Electro-Mechanical Systems (MEMS) technology [3] provide an exciting opportunity for their application as a low-cost alternative in precision manufacturing. The growth of MEMS has been driven by the Industrial Internet of Things (IIoT) revolution [4, 5] which leads the evolution of sensors to smart sensors in manufacturing [6] and intelligent machining processes [7]. MEMS sensors are already in wide usage in vibration sensing applications of large structures e.g. wind turbines, oil rigs, bridges and smart cities of the future [8]. However, metrology aspects related to the accuracy, uncertainty, repeatability and traceability of such MEMS sensors [1] in precision manufacturing have not been explored, so they require performance evaluation to identify parameters which induce sensor uncertainties. [9]. This research focuses on the characterization of measurements from low cost tri-axial accelerometers in terms of of accuracy, uncertainty, repeatability and traceability. Static and dynamic calibration of MEMS sensors was conducted on a calibration test bench using a range of frequencies, while establishing traceability according to the ISO 16063 [10, 11] and IEEE-STD-1293-2018 [12] standards. The work also encompasses reliability evaluation of sensors in aspects pertaining to digital transmission of recorded data [13] in context of Industry 4.0 [5]. The outcomes of this research is an example application of applying a metrological approach when selecting sensors in Industry 4.0 application [14].

2. Methodology

The performance evaluation and characterization tests for low cost accelerometers were conducted by establishing traceability according to the ISO 16063-21 [11] and ISO 16063-11 [10] standards. These standards define procedures for calibration of vibration sensors by comparing their results to a reference transducer [15] and laser interferometry [16]. These methods are suitable for traditional vibration sensors, so were adapted for the MEMS sensors using IEEE-STD-1293-2018 [12].

A series of static and dynamic calibration tests were performed based on the aforementioned standards. The static tests were performed for baseline performance and noise characterization of sensors in a vibration-isolated and temperature-controlled environment. The dynamic tests were performed using sine sweep testing [16] in a frequency range of 5 Hz to 1 kHz. The frequency range was selected to cover most structural resonance frequencies for the majority of machine tools in industry. This range would also cover frequencies of interest for most rotary components on a machine tool, such as bearing rotational speeds, ball-pass and ball-spin frequencies, excluding high-speed spindles. Each test was conducted for a duration of 20 seconds. To ensure repeatability according to industry practise, each set of readings was repeated five times.

2.1. Experimental Setup

An industrial grade tri-axial digital MEMS sensor (ADXL355) [17] was selected as a low cost vibration sensor for this investigation. While there are a great many MEMS alternatives at even lower cost, this provided high resolution (18 bit) on chip ADC to give the required sensitivity that may be expected from traditional accelerometers while also providing the digital communication option (I2C/SPI) for convenient data acquisition. A single axis IEPE accelerometer (PCB 353B03) [18] was employed as a reference transducer in the experiment. A Renishaw XL-80 [19] laser interferometer was used as traceable reference in acceleration measurement mode. The sensors were mounted on a 10 mm aluminium plate and secured using bolts, while the sensor cables were secured using adhesive clamps.

Finite Elements Analysis (FEA) of the plate was carried out before testing to ensure the Centre of Gravity is in line with the mounting position and uniform vibration pickup. The MEMS sensor was housed in a specially designed, 3-D printed case (PLA) and FEA was carried out for the housing to ensure accurate vibration pick-up for the selected frequency range. The first vibration mode of the housing was found to be 7 kHz, only when simply supported where the fixings are at either end as seen in Figure 1. During FEA, a void underneath the housing was created to exaggerate poor contact, this may be due to non-flat surfaces. In Figure 1 (Right) the section view highlighting the compression of the MEMS device between lid and base has also been presented. The results of both FEA simulations showed that the plate and housing had sufficient uniformity and transmissivity that both sensors would experience the excitation signal and that neither would have the signal attenuated at their point of location.

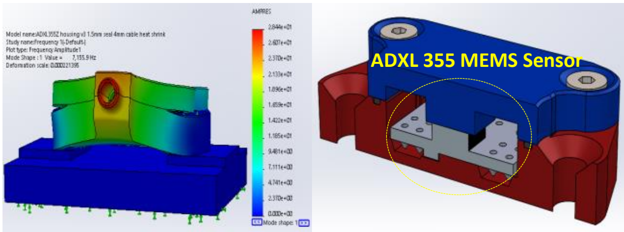

Figure 1. MEMS Housing Element FEA

Temperature was monitored during the experiment using digital temperature sensors (Maxim DS18B20), whereby recording sensor and environmental temperature variations. The configuration of the setup can be seen in Figure 2.

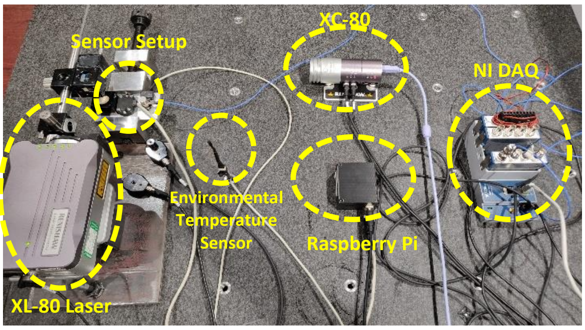

Figure 2. Experimental Setup

All three measuring systems (MEMS, laser and IEPE accelerometer) had separate Data Acquisition Systems (DAQs) which were recorded to a single computer to aid synchronisation. The data from the MEMS sensor was recorded and transmitted at a baud rate $7{\times}10^5$ bits/sec through a Raspberry Pi 3 Model B+ processor wirelessly to a PC through implementation of I2C serial protocol. Laser measurements were recorded using Renishaw's QuickViewXL via USB interface to the PC. The data from the IEPE accelerometer was acquired using an National Instruments DAQ. The tests were synchronised across DAQs to ensure correct timing information for recorded data. The nominal range of the MEMS sensor was set to be ±2 g (where g=9.81 m/s^2) to ensure high sensitivity operation, while the IEPE sensor was used in its nominal operating range of ±500 g. The sampling rate was set to be 2 kHz across all sensor acquisition systems to ensure comparability of results in the analysis phase of the experiment and to ensure fulfilment of nyquist criterion for dynamic test frequencies in current application.

2.2. Static Test

Static tests were conducted to characterize the noise and baseline parameters of the MEMS sensor in comparison to the chosen transfer standard (laser interferometer) and reference transducer (IEPE). The test was conducted in a temperature-controlled environment of ±1 °C on a vibration-isolated and stable granite CMM bed. This was done to ensure surrounding vibrations and background noise be minimized to accurately measure the vibration pick-up from sensors.The setup was allowed to stabilize after installation for a duration of 24 hrs to minimize the effect of environmental and self-heating effect on sensors, which may cause sensitivity drift. For example, nominal sensitivity of 10 mV/g of the IEPE based sensor in the experiment could vary up to ±1 % due to variation of temperature in operating range of -54 °C to +121 °C [18], while the MEMS vibration sensor's output can vary 0.15 mg/°C or ±0.01 %/°C [17]. To ensure accurate laser measurements and minimizing the drift caused by the refractive index of air, the air gap between the reflector and laser was minimized to <20 mm. The cabling of the setup was also secured using adhesive clamps such that it would not induce or transmit unwanted vibrations to the experiment. The configuration of static tests can be seen in Figure 3.

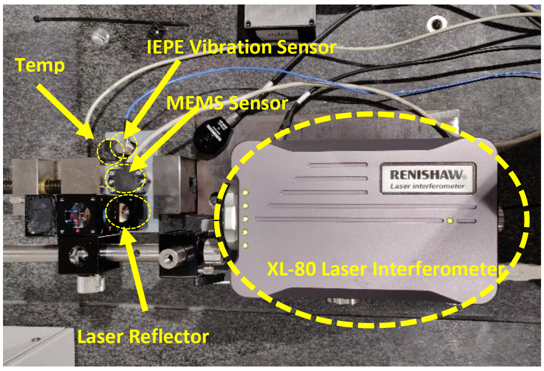

Figure 3. Static Test Configuration

2.3. Dynamic Tests

The dynamic calibration setup was created to perform dynamic tests using sine sweep testing, as seen in Figure 4. The setup consist of the aluminium plate used in the static tests mounted securely on an electrodynamic shaker system (TIRA 500). In this experiment, the sensors were excited in only one axis of movement, namely the Z-Axis, as a proof of concept. The input to the shaker is from a signal generator via an amplifier and only the frequency of generated waveform is modified, whilst keeping amplifier power constant. The power output from amplifier was set at 20 mW. The power settings were chosen to prevent overloads in sensing, especially in the case of

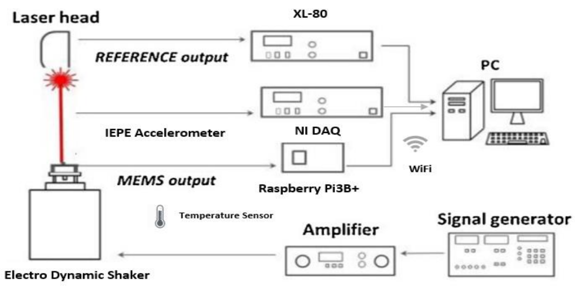

Figure 4. Dynamic Test Configuration

the MEMS sensor. The sixteen frequencies on which the sine sweep testing was conducted are given in the first column of Table 2. The sampling rate set in the experiment followed the Nyquist criterion to ensure good spectral analysis at later stage of the experiment. For each frequency, the test was conducted 5 times for repeatability, therefore in total 80 readings of 20 secs duration each were recorded by the sensors.

3. Data Analysis

A baseline noise and uncertainty analysis was carried out for all the tests. In addition, spectral analysis was carried out for all dynamically recorded data to compare amplitude and frequency response of each sensor with nominally generated sinusoidal waveforms. For the reliability evaluation in terms of digital transmission of recorded data of the MEMS sensor, the assumed sampling rate and achieved sampling was also examined to characterize the latency and accuracy of recorded and transmitted data. The results from baseline measurements and uncertainty evaluation based on the GUM guidelines [20] for static tests are tabulated in Table 1, which can be expanded for uncertainty values in the future, it also shows promising results for noise floor analysis as MEMS based sensor outperforms other sensors with good noise rejection. However, it must be noted standard deviation values can be affected by drift of sensors due operation over time while, these results are based on test duration of 20 secs only. Further investigation in future is required to investigate long term effects of noise, drift and temperature in case of MEMS sensor measurements for industrial applications. The results from the spectral analysis of the dynamic tests are tabulated in Table 2. The spectral analysis was conducted by computing the N-point (N=1024) Fast Fourier Transform (FFT) of the recorded data in MATLAB. The sampling rates of MEMS sensor for transmission reliability evaluation and digita latency computation are presented in Table 3.

Table 1 Uncertainty Evaluation of Sensors for Static Tests ($g = 9.81 m/s^2$)

Sensor	Mean (g)	Standard Deviation S.D (g)
Laser XL-80	0.0003	0.0111
IEPE PCB353B03	0.01535	0.0037
MEMS ADXL355	-7.6751E-16	0.0005

Table 2 Spectral Analysis using FFT of Sensors

Experiment Frequency (Hz)	Generated Frequency (Hz)	Laser XL-80 (Hz)	IEPE PCB 353 (Hz)	MEMS ADXL355 (Hz)
0	0	259.8	0	0
5	5.02	257.8	4	5.674
10	10.20	9.766	10	10.58
25	25.06	25.39	26	25.2
50	50.59	50.78	50	50.22
75	75.37	74.22	76	75.09
100	100.3	99.61	100	100.1
200	200.3	199.2	198	200.2
300	299.6	302.7	302	300.8
400	400.8	400.4	402	400.7
500	501.2	500	500	329.3
600	601.3	599.6	600	237.5
700	701	699.2	700	129.03
800	802.1	800.8	800	24.16
900	900.9	902.3	904	74.52
1000	1000	998	1000	159.8

Table 3 Sampling Rate for MEMS ADXL355

Experiment Frequency (Hz)	Maximum Rate (Hz)	Average Rate (Hz)	Minimum Rate (Hz)
0	896.22	822.90	59.15
5	908.25	830.41	130.1932
10	913.20	833.31	75.36
25	910.81	832.40	128.29
50	909.83	829.45	130.62
75	900.06	818.48	90.88
100	894.49	819.94	123.80
200	905.71	830.08	128.53
300	902.58	825.81	35.75
400	904.33	827.18	82.84
500	905.89	828.66	41.28
600	920.00	835.60	38.38
700	910.81	832.60	130.44
800	903.36	824.08	129.77
900	909.03	829.40	88.20
1000	923.45	843.90	92.54

4. Results and Discussion

Based on the data analysis the results relating to spectral analysis of MEMS sensor data in comparison to IEPE and Laser sensors are visualized and discussed in this section. Moreover, based on the sampling rate offered by MEMS sensor the results and aspects affecting reliability evaluation in terms of digital transmission of recorded data are also presented.

4.1. Spectral Analysis

For comparibility of MEMS frequency response with the results from IEPE and Laser sensors, they are presented on a single FFT plot for frequencies of 300 Hz and 700 Hz respectively. The frequencies have been chosen from Table 2 to depict an accurate sensor response i.e. 300 Hz and the response of MEMS when subject to aliasing due to sampling rate limitations. The FFT plots are presented in Figure 5 and Figure 6.

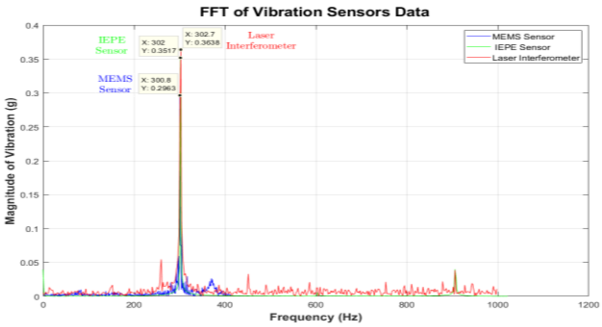

Figure 5. FFT of Vibration Data from Sensors @ 300Hz

Considering Figure 5 and data from Table 2, it can be visualized that on X-axis that the frequency of generated sine waveform i.e. 299.6 Hz is more accurately sensed by MEMS sensor as compared to IEPE and Laser sensors i.e. 302.7 Hz and 302 Hz. However, while considering the magnitude of FFT on Y-axis of figure MEMS records a value of 0.2962 g in comparison of other sensors which record 0.36376 g and 0.35168 g. The discrepancy in magnitude results can be attributable to high sensing mode of MEMS sensor i.e. ±2 g (where $g=9.81 m/s^2$) and noise filtering implemented as part of internal MEMS design. It is to be noted that peak values in FFT are strongly affected by sampling frequency of instruments. The variation in frequency can also be partially attributable to mechanical aspects of shaker accurately recorded by Laser sensor as it is the primary source of traceability, although frequency sensed by MEMS is close to original generated signal but can be misleading. Considering Figure 6, Table 2 and Table 3, it can be seen MEMS records erroneous data due aliasing errors, therefore it depicts an in-correct frequency of 129.63 Hz in comparison to 700 Hz and

699.2 Hz. The results highlight that a data loss occurs in recorded signal due to the overlapping of signal frequencies as Nyquist criterion is not fulfilled in the test condition.

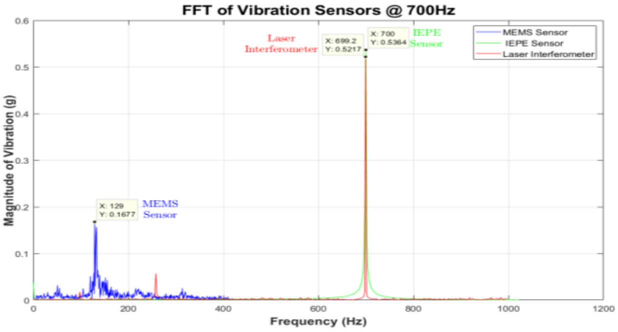

Figure 6. FFT of Vibration Data from Sensors @ 700Hz

4.2. Sampling Rate

Sampling rate or frequency of MEMS sensor data acquisition system emerges as an important aspect to consider while taking sensor measurements. The sampling rate is fixed at 2kHz in case of IEPE and Laser sensors while, in the current setup the sampling rate for MEMS is found to be variable based on the overhead due to data processing and transmission on current DAQ. The sampling rate for300 Hz test is visualized in Figure 7

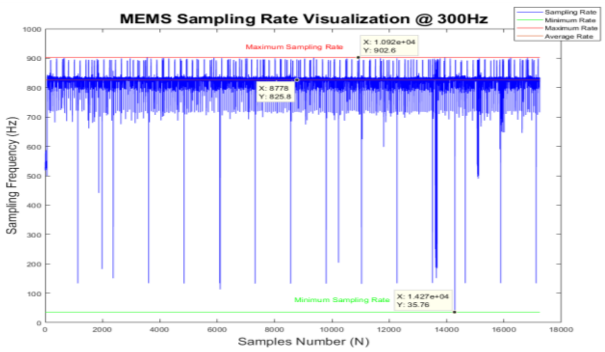

Figure 7. Sampling Rate of MEMS Sensor @ 300Hz

Considering Table 3 and Figure 7 the sampling rate of MEMS sensor system varies from 35.75 Hz to 902.58 Hz. The sources of these variations lead to data loss, attributable to I2C communication and DAQ processing errors. However, the FFT was computed based on mean sampling rate i.e. 825.81 Hz, found most suitable for accurate results. Considering all tests an average rate of 829 Hz was calculated, therefore MEMS sensor would sense frequencies below 414 Hz accurately in the current DAQ-sensor setup. It was found that performance of MEMS sensor is typically affected by acquisition system in a significant way. The issue was overcome in future implementations of the sensor DAQ setup by reducing cable length to less than 0.5 m and implementation of multi-core processing on Raspberry Pi 3B+ for improved I2C serial communication for reduced latency in data transmission, this lead to achieving a sampling rate of 2000 Hz or 2 kHz, however it is a work in progress and requires further investigation for optimization on machinery with high energy systems such as drive motors.

5. Conclusions

This work focuses on performance evaluation of low cost MEMS sensors for use in precision engineering applications. The characterization of MEMS sensor was done through performing static and dynamic traceability tests in accordance to the ISO 16063 and the IEEE-STD-1293-2018 standards. The MEMS sensor setup was able to to accurately provide measurements for low magnitude vibrations in frequencies up to 400 Hz with good noise rejection,while comparison testing on machine tool was aided by measurements from Laser and IEPE sensors. The current setup has limitations due to sampling rate which leads to uncertainty in digital transmission of recorded data. Future work requires further exploration of aspects affecting uncertainty for MEMS sensors. MEMS sensors provide exciting opportunities in application areas of Industry 4.0 and evolution to smart sensors due to their low-power, low-cost and ultra low noise aspects, while digital aspect in data sensing and processing are still to be overcome. Improved results can lead to building self-calibration setup in sensor-nets while employing MEMS sensors on machine tools as a viable low-cost and reliable option for servitization, condition monitoring, smart machining purposes.

Acknowledgements

The authors gratefully acknowledge the UK's Engineering and Physical Sciences Research Council (EPSRC) funding of the Future Metrology Hub (Grant Ref: EP/P006930/1).

References

[1] M. Galetto, A. Schiavi, G. Genta, A. Prato, and F. Mazzoleni, "Uncertainty evaluation in calibration of low-cost digital MEMS accelerometers for advanced manufacturing applications," *CIRP Annals,* 2019.

[2] K. Szipka, A. Archenti, G. W. Vogl, and M. A. Donmez, "Identification of machine tool squareness errors via inertial measurements," *CIRP Annals,* vol. 68, no. 1, pp. 547-550, 2019/01/01/ 2019.

[3] J. R. Evans *et al.*, "Performance of Several Low-Cost Accelerometers," *Seismological Research Letters,* vol. 85, no. 1, pp. 147-158, 2014.

[4] E. Ahmed *et al.*, "The role of big data analytics in Internet of Things," *Computer Networks,* vol. 129, no. P2, pp. 459-471, 2017.

[5] A. Gilchrist, *Industry 4.0: The Industrial Internet of Things*, 1 ed. (no. Book, Whole). Berkeley, CA: Apress, 2016.

[6] F. Tao, Q. Qi, A. Liu, and A. Kusiak, "Data-driven smart manufacturing," *Journal of Manufacturing Systems,* vol. 48, pp. 157-169, 2018/07/01/ 2018.

[7] J. Chen *et al.*, "Toward Intelligent Machine Tool," *Engineering,* 2019/07/22/ 2019.

[8] A. Sabato, C. Niezrecki, and G. Fortino, "Wireless MEMS-Based Accelerometer Sensor Boards for Structural Vibration Monitoring: A Review," *IEEE Sensors Journal,* vol. 17, no. 2, pp. 226-235, 2017.

[9] G. D'Emilia, A. Gaspari, and E. Natale, "Evaluation of aspects affecting measurement of three-axis accelerometers," *Measurement,* vol. 77, pp. 95-104, 2016.

[10] B. ISO, "BS ISO 16063-11:1999: Methods for the calibration of vibration and shock transducers. Primary vibration calibration by laser interferometry," ed: British Standards Institute, 2001.

[11] B. ISO, "BS ISO 16063-21:2003: Methods for the calibration of vibration and shock transducers. Vibration calibration by comparison to a reference transducer," ed: British Standards Institute, 2003.

[12] IEEE, *IEEE Std 1293-2018 (Revision of IEEE Std 1293-1998): IEEE Standard Specification Format Guide and Test Procedure for Linear Single-Axis, Nongyroscopic Accelerometers* (IEEE Std 1293-2018). IEEE, 2019.

[13] B. I. UK, "Digital manufacturing – Trustworthiness and precision of networked sensors – Guide," *BSI,* 2019.

[14] D. G. Pascual, P. Daponte, and U. Kumar, "HANDBOOK OF INDUSTRY 4.0 AND SMART SYSTEMS," (in English), 2019.

[15] G. D'Emilia, A. Gaspari, F. Mazzoleni, E. Natale, and A. Schiavi, "Calibration of tri-axial MEMS accelerometers in the low-frequency range - Part 1: Comparison among methods," *Journal of Sensors and Sensor Systems,* vol. 7, no. 1, pp. 245-257, 2018.

[16] N. Garg, O. Sharma, A. Kumar, and M. I. Schiefer, "A novel approach for realization of primary vibration calibration standard by homodyne laser interferometer in frequency range of 0.1Hz to 20kHz," *Measurement,* vol. 45, no. 8, pp. 1941-1950, 2012/10/01/ 2012.

[17] A. Devices, "ADXL354/ADXL355 Low Noise, Low Drift, Low Power, 3-Axis MEMS Acceleromters Data Sheet (Rev. A)," 2018.

[18] P. Piezotronics. (2019). *PCB 353B03 Single Axis Accelerometer Data Sheet*. Available: https://www.pcb.com/products?m=353B03

[19] O. Samoylenko, O. Adamenko, and V. Kalynichenko, "The Method and the Results of the Direct Comparison of the Laser Interferometers Renishaw Xl-80," *Metrology and instruments,* no. 4, pp. 15-21, 2018.

[20] J. Committee Guides Metrology, *Evaluation of measurement data – Guide to the Expression of Uncertainty in Measurement (GUM 2008)*. 2008.