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# Managing the sampling rate variability of digital MEMS accelerometers in dynamic calibration

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***Abstract*** **— The use of sensors with digital interface, within large or dense sensor networks, is nowadays widespread in many scientific and technological applications: from more traditional applications, such as infrastructure monitoring and predictive maintenance, up to the advanced ones, such as smart manufacturing, IoT, Machine Learning, and other emerging fields of fast-real-time interconnections, within the framework of digitalization. The technical and functional performance of these sensing infrastructures, if accurately identified, allows to enhance the trustworthiness, safety, and accuracy of the managed processes; based on metrological characterizations and calibration, it is possible to provide the actual sensitivity of digital sensors with respect to reference physical stimuli, within the proper uncertainty budgets and suitable covering factors. At present days, metrological characterization and proper calibration of digital sensors is still a technical and methodological challenge and several studies are oriented along with this perspective. In this paper, the sampling rate variability – depending on MEMS analog-to-digital converter, external microcontroller internal clock and their interaction – of digital MEMS accelerometers in dynamic calibration is investigated. The sampling rate variability is evaluated among 25 sensors of the same batch, and within every single sensor in time, and methods to manage the associated uncertainty and to avoid mismatches in calibration, are proposed and discussed.**

**Keywords—Dynamic calibration, digital MEMS accelerometer, sampling rate**

## I. INTRODUCTION

In the framework of digitalization, the trustworthiness of data (and big data) provided by dense sensor networks and the reliability of digital sensors, in terms of accuracy up to traceability, are essential requirements for safe, trustworthy, and suitable development of these sensing infrastructures, nowadays widely employed in many advanced engineering applications, including managing of operations and processes, functional monitoring and geo-environmental survey [1-3]. The opportunity of using very large (or dense) networks of digital sensors (in particular MEMS/NEMS sensors) opens up new and interesting perspectives in the field of measurement science and engineering control, until now unsustainable, in terms of costs and management. Moreover, in the last years, the technical performance of digital sensors and the improved big data flows managing, are greatly evolved, thus several metrological properties, such as accuracy, reliability, and traceability become emerging quality attributes of interest, for both manufacturers and end-users [4-10].

The possibility of including the indications provided, in form of digital output, by digital sensors (and by the entire infrastructure of sensors, from nodes to hubs, up to data transmission and processing) within the metrological traceability, then to the International System of Units (SI) of the Metro Convention, is a fundamental objective of the recent metrological research, as indicated in the Bureau International des Poids et Mesures (BIPM) strategy document for the future, and strategic plans of several Consultative Committees within it [11-12]. Therefore, several National Metrology Institutes (NMIs) worldwide oriented their activities toward the calibration of digital sensors and the related sensing infrastructures [13].

Nevertheless, at present, there are not still technical standards for the calibration of sensors with digital output and digital interface, thus end-users will usually get neither a calibration certificate nor a traceability statement from the manufacturer, although the sensitivity is adjusted during the production process [14]. As a consequence, calibration and traceability of sensors with digital outputs are still a challenge in the field of applied metrology, under several technical, procedural, and practical points of views, since «these technologies have different mounting requirements, use different testing and calibration protocols, and use digital interfaces for data and communications» [11], and proper (and agreed) methodologies and analyses need to be developed and applied, to identify and quantify the actual sensitivity values of digital sensors. Not only from the purely technical point of view some issues need to be solved, but also the «semantics» related to the metrology applied to digital sensors, is still lacking, and sometimes misinterpretations of technical terms occur. To avoid misunderstandings, the meaning of terms used in this paper is referred to the International Vocabulary of Metrology (VIM).

Recently University of L'Aquila (UNIVAQ) and Italian Institute of Metrological Research (INRIM) have developed two independent specific calibration systems and analysis protocols, for the metrological determination of the sensitivity of digital MEMS accelerometers (in the frequency domain), traceable to the SI, and comparable. Previous investigations gave relevant information regarding traceability, «digitized sensitivity», uncertainties assessments, comparability, and reproducibility of calibration results in the two laboratories [15]. In that work it was observed a variability of the sampling rate (generated by the interaction between the MEMS analog-to-digital converter and the external microcontroller which provides the internal clock) of each digital MEMS accelerometer, within a large sample, both in terms of absolute value (among the sensors) and in terms of "fluctuations" over time (within the sensor). The proper identification of sampling rate is a priority in dynamic calibration, since it affects the measurement accuracy and precision of both amplitude and phase of the device under test (DUT), with respect to reference physical standards, and SI. The aim of this investigation is twofold: from one hand it allows to evaluate the actual variability of the sampling rate of nominally identical MEMS sensors from a same batch, and on the other hand it allows to quantify the influence of such variability on calibration sensitivity. Such investigations are performed by both laboratories with their independent calibration systems and results are compared.

## II. DIGITAL MEMS AND DIGITAL OUTPUT

DUTs investigated in this work, are 25 commercial low-power digital 3-axis MEMS accelerometers (ST, model LSM6DSR [16]). The DUT is composed of a MEMS accelerometer sensor, a power supply, a charge amplifier, and an analog-to-digital converter, connected by a serial cable to a separated external microcontroller (ST, model 32F769IDISCOVERY [17]), to acquire digital data and to provide the required power supply and clock to the MEMS accelerometer. The signal is acquired through a Serial Peripheral Interface (SPI), which is a synchronous serial communication interface used for connecting digital sensors. The 1-bit signal from the ΣΔ-ADC is then converted through a decimation process and a low pass filter into a standard 16-bit-signed PCM (Pulse Code Modulation) signal with a nominal sampling frequency rate of 1660 Hz. The decimal-converted bit-string of the PCM signal is the indication of the DUT to be correlated to the reference physical stimuli, in this case, acceleration in $m/s^2$, and to the SI. Thus, in the following the measured «digitized sensitivity» of DUTs is expressed in terms of $D_{n\text{-bit}}/(m/s^2)$, i.e. decimal referred to the *n*-bit 0/1 binary sequence (eventually with positive or negative sign) of PCM signal, in analogy to the typical sensitivity of analog accelerometers, expressed in linear units, as $V/(m/s^2)$, or $pC/(m/s^2)$. By using this notation, the amplitude values of DUTs range between $-2^{16-1}=-32768$ $D_{16\text{-bit-signed}}$ and $+(2^{16-1}-1)$ $=+32767$ $D_{16\text{-bit-signed}}$, where the digit unit is a signed 16-bit sequence converted into a decimal number.

The «digitized sensitivity» $D_{n\text{-bit}}/(m{\cdot}s^{-2})$, as calibration result, is not in conflict with the «adjusted sensitivity» provided by manufacturers, expressed in terms of Least Significant Bit (LSB) referred to *g*, i.e., *g*/LSB, as commonly used according to IEEE Standard, but it represents a further quality parameter of the DUT, allowing to provide the accuracy of measurements, with reference to the static and dynamic calibration.

However, in dynamic calibration, the digitized sensitivity of DUTs, depends on the sampling rate generated by the interaction between the MEMS analog-to-digital converter and the external microcontroller which provides the clock, thus it is a time-dependent quantity. To define the DUT digitized sensitivity, from dynamic calibration, it is necessary to correlate frequency-dependant reference acceleration amplitude with the indication provided in form of digital output form DUT itself, that is generated according to the internal sampling rate (nominally 1660 Hz, for this DUTs). On the contrary, in static calibration, sampling rate does not affect the calibration results, since the DUT sensitivity determined with respect to gravity filed, is time-independent.

As a matter of fact, as observed in previous investigations, the effective sampling rate generated by the interaction between the MEMS and the external microcontroller shows "fluctuations" in time, e.g., due to temperature drift or other internal processes in the sensor [18]. Generally, the clock generation and the sampling process for the timing generator are inaccessible from the outside, since integrated within the devices.

## III. SAMPLING RATE EVALUATION AT UNIVAQ AND AT INRIM

Comparison of the sensitivity values between the 25 MEMS measured by UNIVAQ and INRIM independent vibration amplitude calibration systems was previously carried out at 3 frequencies, namely 3 Hz, 6 Hz and 10 Hz, by comparison to a reference transducer (in analogy to ISO Standard 16063-21 [19]) as thoroughly described in [5,6,15,20]. In those works, it was found a sampling rate variability within the MEMS (with time) and among the different MEMS. However, a comparison was not performed and described in depth.

Given the two different calibration systems, the sampling rate evaluation is also performed differently.

### *A. UNIVAQ*

The method used by UNIVAQ for the calculation of the sensitivities is based on the FFT of MEMS and reference signals. The root sum squared of the amplitudes of the spectrum in the range centred at the oscillation frequency and width ±10%, is calculated. Then, the sensitivity is obtained by dividing the values thus calculated for MEMS and reference. Three repeated tests have been carried out for each frequency, each accelerometer and each axes.

For the calculation of the real sampling rate of the MEMS accelerometers, the distance between peaks, that is the period of the sinusoidal signal, has been evaluated, in terms of number of samples, over 90 cycles for each acquisition. These values are, then, multiplied by the oscillation frequency (3, 6 or 10 Hz, in this case); the sampling rate is, finally, obtained by averaging over groups of three values, which has been considered a suitable trade-off between keeping under control the effect of noise and being able to monitor the variability of sampling rate within a single MEMS.

In fact, noise affects the calculation of the sampling rate by moving the peaks of acceleration time diagram: this effect is reduced remarkably when the signal to noise ratio is higher (vibrations at 6 Hz and 10 Hz). Table 1 shows the effects of averaging and of the signal to noise ratio.

Therefore, 30 sampling rates have been evaluated for each acquisition, thus a total of 810 sampling rates are obtained for each accelerometer (30 values × 3 tests × 3 frequencies × 3 axes). It is observed that *x*-, *y*- and *z*-axes are considered equivalent, from the point of view of the sampling frequency, since the MEMS device is equipped with a single clock on board.

Table 1. Standard deviation of sampling rate [Hz], evaluated on 1, 3, 5 or 10 cycles.

| | 1 cycle | 3 cycles | 5 cycles | 10 cycles |
|---|---|---|---|---|
| **3 Hz** | 23 | 7.8 | 4.8 | 2.5 |
| **6 Hz** | 17 | 5.8 | 3.6 | 2.6 |
| **10 Hz** | 15 | 5.2 | 3.1 | 1.8 |

### B. *INRiM*

INRiM calibration method consists in the acquisition of the temporal vibration signals from the MEMS output, generated by the vibrating table and expressed in $D_{16\text{-bit-signed}}$, at 3 Hz, 6 Hz and 10 Hz, consecutively. To get the sensitivity value, the digital signal is processed, for each specific frequency, by applying a first-order Butterworth band-pass filter, centred at the frequency of interest with a fractional bandwidth of 10%, to the temporal signals and, subsequently, by computing the Root Mean Square (RMS), in order to remove the off-set due to gravity and the influence of background vibrations. This value is then compared to the known reference to get the sensitivity value, expressed in $D_{16\text{-bit-signed}}/(\text{m/s}^2)$.

The actual sampling frequency of every MEMS is evaluated by counting the number of samples occurring between two consecutive peaks of the sinusoidal signal. In particular, 9 pairs of consecutive peaks (three for each generated frequency, randomly chosen approximately in the initial, central and final parts of the signal), are used for the evaluation of the sampling rate and its variability in time of each MEMS, thus a total of 225 sampling rates are obtained (25 MEMS × 9 pairs). By way of example, the temporal signal at 6 Hz of MEMS #1 with a focus on a pair of peaks is shown in Fig. 1.

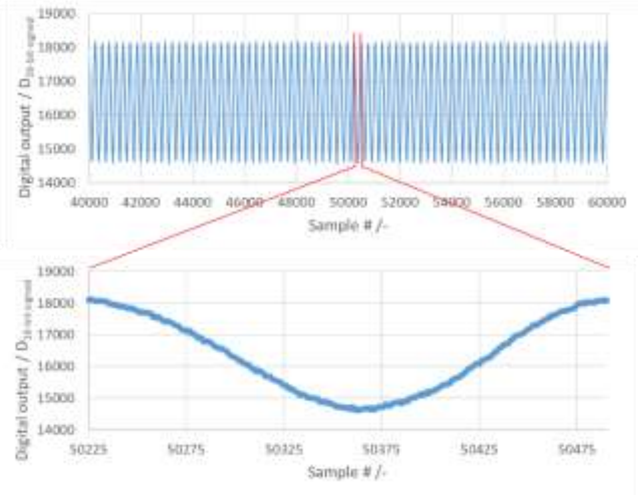

Fig. 1. Temporal signal obtained for MEMS#1. A pair of peaks occurring at 6 Hz are enlarged.

The identification of the peaks is performed through a fit with a Lorentzian function. This allows to uniquely identify the exact sample of the peak with an uncertainty less than 0.2 samples, therefore negligible for the purpose of the work. An example is shown in Fig. 2.

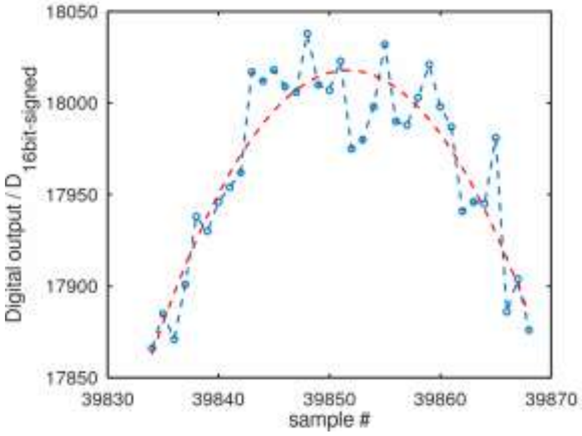

Fig. 2. Lorentzian fit of a peak.

## IV. RESULTS

### A. *UNIVAQ*

Results obtained by UNIVAQ laboratory are summarized in Fig. 3, as box plots.

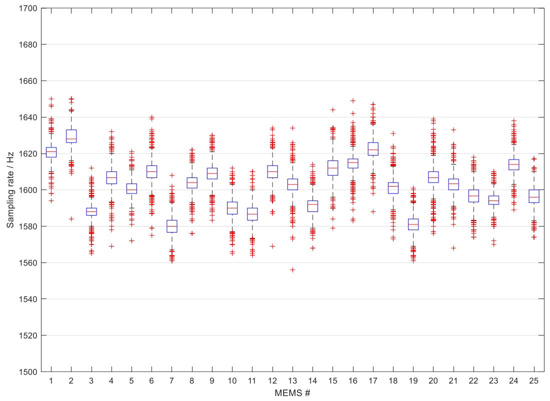

Fig. 3. Sampling rates within and between the different MEMS, as evaluated by UNIVAQ.

Fig. 4 also shows the distribution of the sampling rate calculated for MEMS #4, as an example; Fig. 5 represents the frequency distribution of the measured sampling rates of all MEMS sensors.

The estimated sampling rate is not constant neither within nor between MEMS accelerometers and, on average, it is equal to 1603 Hz, then lower than the nominal value, 1660

Hz.

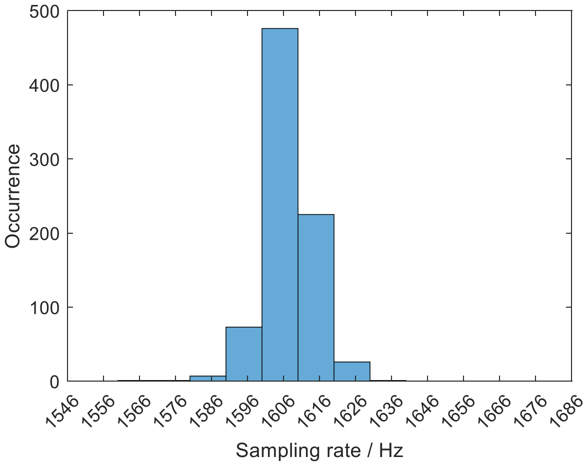

Fig. 4. Frequency distribution of sampling rate for the accelerometer #4.

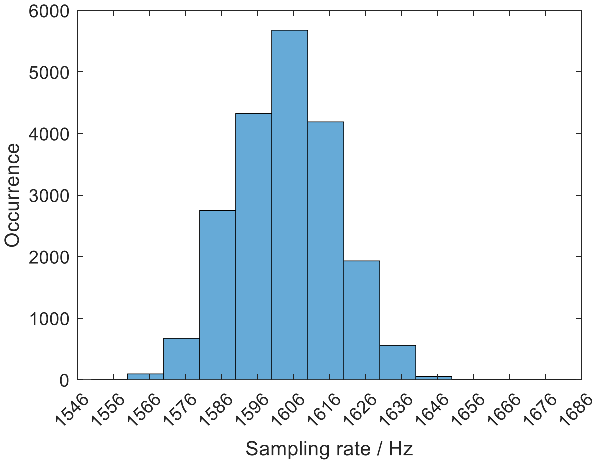

Fig. 5. Frequency distribution of the sampling rates of all MEMS.

The variability among different MEMSs is larger than the variability within the MEMS (standard deviation of 13 Hz vs 6.5 Hz, on average). Performing the analysis of variance, it is found that the variability among the different MEMS sensors is significant ($p<0.05$) whereas the variability within each MEMS is not significant ($p>0.05$).

A check on the average sampling rates, as determined by the described method (Method 1), has been carried out, by means of a second method (Method 2), based on the evaluation of the peak frequency of the FFT. It is, in general, not coincident with the real oscillation frequency, due to differences between the nominal and actual average sampling rates.

On the basis of this value, the average sampling rate can be obtained as follows:

$$sr_r = f_r \cdot sr_n / f_m \quad (4)$$

where:
$f_m$: measured peak frequency
$f_r$: real oscillation frequency (3, 6 or 10 Hz)
$sr_n$: nominal sampling rate
$sr_r$: real sampling rate

This method does not allow to determine the variability of the sampling rate along an acquisition, but only its average value.

A comparison between the two methods is shown in Fig. 6, where the error bars represent the standard deviation of data: the average values of the sampling frequencies are in agreement.

Fig. 6. Comparison between average sampling rates, as calculated by Method 1 and Method 2.

## B. INRiM

Results obtained at INRIM are summarized in Figs. 7 and 8, which respectively represent the frequency distribution and the box-plots of every MEMS of the measured sampling rates. Values range between 1540 Hz and 1680 Hz, which represent the minimum and maximum values of all data, within and among the MEMS. The overall average value is 1602 Hz, with a standard deviation of 16 Hz.

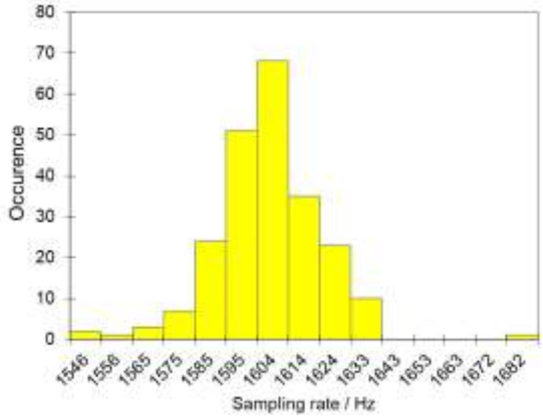

Fig. 7. Frequency distribution of the sampling rates of all MEMS.

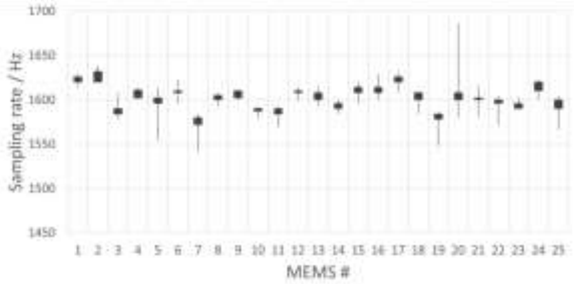

Fig. 8. Sampling rates within and among the different MEMS, as evaluated by INRiM.

It is found that the sampling rate is not constant neither within (i.e., in time) nor between the MEMS and, in general terms, is lower than the nominal value declared by the manufacturer, i.e. 1660 Hz. In particular, the variability between the MEMS (standard deviation of mean values is equal to 13 Hz) is larger than the variability within the MEMS (mean value of the standard deviations is equal 9 Hz). This is also confirmed by performing the analysis of variance, at a confidence level of 95%. It is found that the variability among the different MEMS is significant ($p<0.05$) whereas the variability within each MEMS is not significant ($p>0.05$).

## V. DISCUSSION

Probability density functions of the sampling rates evaluated by the two laboratories, depicted in Fig. 9, show a very similar behaviour.

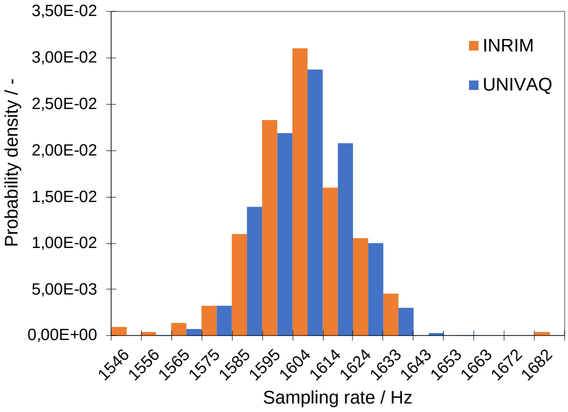

Fig. 9. Probability density functions of the sampling rates of the 25 MEMS evaluated by UNIVAQ and INRIM.

Comparison of the results of each MEMS between UNIVAQ and INRIM is performed with the normalized error $E_n$, according to ISO/IEC 17043:2010 [39], which is defined as the ratio of the absolute difference between two mean values compared to the root sum square of the associated expanded uncertainties at a confidence level of 95% (k=2). The data can be considered compatible when $E_n<1$. Normalized errors reported in Fig. 10 are lower than 0.30 for all the 25 MEMS, therefore results from the two laboratories are highly compatible.

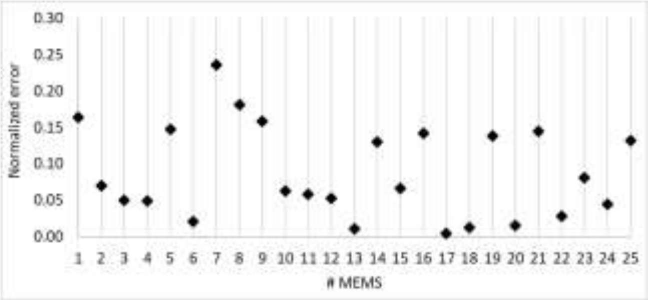

Fig. 10. Normalized errors between INRIM and UNIVAQ.

Furthermore, through the analysis of variance, it is found that the variability among the different MEMS is significant whereas the variability within each MEMS is not significant. This means that, although we do not know the interaction processes for data acquisition between the MEMS and the microcontroller, which for us are a black-box as a whole, the variability is likely due to an intrinsic characteristic of the MEMS itself since the microcontroller is the same during all measurements. Moreover, it is observed that the sampling rates are lower than the nominal one declared by the manufacturer, i.e. 1660 Hz.

In the end, the sampling rate variability within the MEMS has to be considered as a source of uncertainty in the evaluation of the sensitivity of MEMS accelerometers because can affect the results in filtering processes. To provide a suitable amplitude calibration it will be therefore necessary to manage the effects of a variable sampling rate and to evaluate its impact on the overall uncertainty [21, 22].

## VI. CONCLUSIONS

The aim of this work is to assess the variability of the sampling rate of nominally identical MEMS accelerometers, and to quantify the influence of such variability on the calibration results. Such investigations are performed by two different laboratories with independent calibration systems and methods for data processing.

The sampling rate of 25 MEMSs of the same batch has been evaluated and the results show that it is not constant neither within nor between sensors and, on average, it is lower than the nominal value declared by the manufacturer, i.e. 1660 Hz.

The variability among MEMS accelerometers results to be significant.

Furthermore, a good agreement between the results obtained by the two laboratories has been observed.

The development of the work involves the evaluation of the impact of the estimated variability of the sampling rate on the assessment of the sensitivities, in terms of uncertainty.

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