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RELIABILITY OF DIGITAL MEMS SENSORS: METROLOGICAL CHARACTERIZATION OF ACCELEROMETERS AND MICRO-PHONES

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The reliability of digital MEMS accelerometer and microphone sensors is investigated, on the basis of suitable calibration procedures developed at INRiM, in order to provide the metrological traceability and the proper sensitivity in the digital domain. Nowadays, digital sensing systems, based on MEMS technology, are largely used in a wide range of advanced industrial, environmental, energy and medical applications. The possibility to have many accurate, low-power consuming and low-cost sensors present undoubted advantages, in terms of costs reduction and energy saving, while maintaining high quality in the control processes, monitoring or measurements and being flexible in providing enhanced data collection, automation and operation. Nevertheless, at present, digital MEMS sensors are not always reliable to quantify with adequate accuracy the measured physical phenomena, due to the lack of metrological traceability and sensitivity parameters for digital sensors.

Keywords: digital MEMS, accelerometers, microphones, calibration

1. Introduction

In the last years a large diffusion of digital sensing systems, based on MEMS technology, has been observed. The global MEMS sensor market was valued at $25.7 million in 2018, and is projected to reach $60.6 million by 2026, registering a CAGR of 10.4% from 2019 to 2026 [1]. The increasing popularity of IoT in semiconductors, increasing demand for smart consumer electronics and wearable devices, and growing adoption of automation in industries and homes, as well as in a wide range of advanced industrial, environmental, energy and medical applications, are some of the significant factors influencing the growth of MEMS market. By way of example, the increasing demand for safety and security in the automobiles is one of the major factors, which is impacting the growth of the market positively. According to the World Health Organization, globally, more than 1.55 million people are killed in road accidents every year, and about 50 million people get injured; MEMS sensors can be used extensively for controlling the airbags in the event of a car accident in the automotive industry. Thus, these sensors play a critical role in improving the safety features of the vehicle and act as the catalyst for the growth of the market [2]. Moreover, in Industry 4.0, a huge number of sensors is needed for an effective implementation of smart factories and intelligent manufacturing systems, by managing automation and enhancing Machine Learning, as well as for early failure detection and predictive maintenance; low-power devices and battery-operated systems are practical and useful for smart cities, for accurate navigation and positioning and in environmental monitoring and survey; accurate and traceable measurements are also of paramount importance in medical applications, in remote surgery and remote diagnoses [3–10].

Furthermore, the use of digital MEMS in extensive sensor-networks (or multi-sensor-networks) presents new and very interesting perspectives in the field of measurement science, allowing to perform observation of phenomena on a very large scale, which until a few years ago were completely unthinkable and inapplicable. The possibility to have accurate, low-power consuming and low-cost sensors present undoubted advantages, in terms of costs reduction and energy saving, while maintaining high quality in the control processes, monitoring or measurements and being flexible in providing enhanced data collection, automation and operation. Moreover, the evolving improvement of the technical performance and the reliability of MEMS sensors are emerging quality attributes of interest for manufacturers, costumers and end-users.

From one hand it has to be said that, at present, technical performance of digital MEMS sensors, in terms of reliability and durability, are not always actually comparable with respect to the traditional analogue devices, on the other hand, the lower accuracy can be compensated by a larger number of points of observation, as well as by opportune coverage factors, suitable for the application under investigation.

Recently, methodologies to evaluate the accuracy and the reliability of digital MEMS sensors, have been implemented, in particular driven by the purposes stated within the emerging metrology requirements for the future in the Strategy 2017 to 2027 document of the Consultative Committee for Acoustics, Ultrasound and Vibration of the "Bureau International des Poids et Mesures" (BIPM), in order to consider these sensors as actual measurement devices [11]. From these purposes, some National Metrology Institutes worldwide (e.g., NIST and INRiM), standardization bodies (e.g., IEEE), as well as some major players (e.g., STMicroelectronics), have directed their efforts in order to provide adequate metrological characterizations of these sensors, in terms of accuracy and traceability against primary standards.

In this paper, the reliability of digital MEMS accelerometer and microphone sensors is investigated, on the basis of suitable calibration procedures developed at INRiM (described in details in [12,13]), in order to provide the metrological traceability and the proper «digitized» sensitivity.

2. The «digitized» sensitivity

A first and not-trivial issue, regarding the metrological characterization of technical performance of digital sensors, is related to the protocols and data managing, of the digital signal output. Indeed, in order to define the actual sensitivity of a digital sensor, it is firstly necessary to identify and quantify the ratio between a physical quantity (to be measured, such as an amplitude of vibration or sound pressure) and a string of bit, instead an electrical quantity, as typically occurs in analogue sensors.

As defined in the International Vocabulary of Metrology [14], the sensitivity of a measuring system, or sensitivity, is the «quotient of the change in an indication of a measuring system and the corresponding change in a value of a quantity being measured». Sensing elements of analogue measuring systems convert the input physical quantities to be measured, into proportional output physical quantities, as "indication". In digital measuring systems, the output physical quantities are directly digitized by the analogue-to-digital converters, and the related "indication" is given in bit-strings; as a consequence, calibration of digital measuring systems is carried out by defining the relation between a 0/1 sequence and a physical quantity. The resulting "quotient" is a digitized sensitivity, since the numerator unit of measurement is related to a n bit 0/1 sequence converted into a decimal number ($\text{Decimal}_{n\text{-bit}}$) and the denominator is the unit of the reference measured physical quantity [15].

Recently, IEEE Standard Association published «IEEE Standard for Sensor Performance Parameter Definitions», providing a comprehensive «framework for sensor performance specification terminology, units, conditions, and limits. This standard is intended for sensor technologies with digital I/O interfaces» [16]. The aim of the IEEE Standard is to define a common methodology for specifying sensor performance to be adopted by the ever-expanding sensor industry. In the IEEE Standard for digital accelerometer, it is proposed to define the sensitivity in terms of Least Significant Bit (LSB) referred to g, i.e., g/LSB. The change in acceleration input corresponding to 1 LSB change in output. Nowadays this definition becomes to be widely adopted by manufacturers in digital sensors datasheets.

Nevertheless, in our opinion, the use of term LSB is partially confusing for digital outputs for two main reasons. First, the actual digital output value is a n-bit 0/1 binary sequence, converted into a decimal number ($\text{Decimal}_{n\text{-bit}}$). Second, although 1 LSB corresponds to 2^0=1 $\text{Decimal}_{n\text{-bit}}$ in most of the cases, according to IEEE Standard, it is not always true, since 1 LSB could correspond to other bit positions, i.e. 2^1=2 $\text{Decimal}_{n\text{-bit}}$, 2^2=4 $\text{Decimal}_{n\text{-bit}}$, or more, depending on the sensor under investigation. Therefore, in the following, the «digitized sensitivity» S_{dgz} of digital MEMS accelerometer and digital MEMS microphones will be expressed, in linear units, as $\text{Decimal}_{n\text{-bit}}$ /m·s^{-2} and $\text{Decimal}_{n\text{-bit}}$ /Pa (or simply $D_{n\text{-}bit}$ /m·s^{-2} and $D_{n\text{-bit}}$ /Pa), by analogy to the typical sensitivity of analogue accelerometers and microphones, expressed in linear units, in terms of V/m·s^{-2} and V/Pa.

2.1 Digitized sensitivity for accelerometers

In metrology, typical sensitivity S of analogue accelerometers is expressed in linear units, in terms of V/(m·s^{-2}). In the same way, the sensitivity of the digital MEMS accelerometer is proposed to be expressed in linear units of $D_{16\text{-bit}}$/(m·s^{-2}), in which $D_{16\text{-bit}}$ represents the decimal number, with positive or negative value (signed), converted from 16-bit binary number. Namely, the signed range of integer values, stored in 16 bits, are −32768 (-1×2^{15}) through 32767 ($2^{15}-1$).

The root-mean-square (*rms*) decimal 16-bit signed values, here expressed as $D_{16\text{-bit}}$, for each specific frequency f, are obtained by applying a pass-band filter, centred at the frequency of interest with a fractional bandwidth of 10%, to the temporal digital signals and, subsequently, by computing the *rms*.

Concluding, the sensitivity of the digital MEMS accelerometer, i.e. the ratio between the digitized *rms* value $D_{16\text{-bit}}$ and the reference acceleration a_{ref}, may be expressed as:

$$S_{dgz} = \frac{D_{16-\text{bit}}}{a_{ref}} \tag{1}$$

In this work, the reference acceleration a_{ref}, is measured by means of a reference accelerometer, with known reference sensitivity S_{ref} (m·s^{-1})/V. By measuring the actual output *rms* reference voltage V_{rms}, for each frequency of interest $\omega=2\pi f$, the related digitized sensitivity of the digital MEMS accelerometer is:

$$S_{dgz} = \frac{D_{16-\text{bit}}}{V_{rms}\cdot S_{ref}\cdot\omega} \tag{2}$$

2.2 Digitized sensitivity for microphones

In acoustical metrology, typical sensitivity S of standard (analogue) condenser microphones is expressed in linear units (mV/Pa or V/Pa) or in logarithmic units (dB re 1 V/Pa). As well as described in the previous section, also the sensitivity of the digital MEMS microphone can be expressed in linear units of $D_{16\text{-bit}}$/Pa or, as commonly used in acoustics, in logarithmic units (dB), according to Eq. (3). Digitized sensitivity level $S_{dgz,dB}$ is arbitrarily referred, in this work, to (2^{15}-1) $D_{16\text{-bit}}$/Pa, which represents the full scale value of the digital signal.

$$S_{dgz,dB} = 20\, log_{10} \frac{S_{dgz}}{2^{15}-1} \tag{3}$$

Where S_{dgz} is the ratio between the digitized *rms* value $D_{16\text{-bit}}$ (the output from the digital MEMS microphone in calibration) and the reference sound pressure level, measured in free field condition, with a calibrated microphone, i.e., $S_{dgz}= D_{16\text{-bit}}/\text{Pa}$.

3. Digital MEMS sensor

In very general terms, a digital MEMS sensor is composed of a sensing element to detect the physical signal to be measured, a programmable gain amplifier to boost the signal and an analog-to-digital converter to digitize the signal into the digital domain. All components are included in a volume of about 10 mm^3 or less. Digital signal is then transferred to a microcontroller for data processing.

3.1 Digital MEMS accelerometer

The digital MEMS accelerometer investigated in this work is a commercial low-power digital MEMS accelerometer (*STMicroelectronics*, model *LSM6DSR* [17]), as shown in figure 1a. It is composed of an accelerometer sensor, a power supply, a charge amplifier and an analog-to-digital converter. The digital MEMS accelerometer is connected by a serial cable to a separated IC-board, in which other electronic components are integrated. The external microcontroller (*STMicroelectronics*, model *32F769IDISCOVERY* [18]) acquires the digital samples and provides the required power supply to the MEMS accelerometer. The signal is acquired by means of a Serial Peripheral Interface (SPI), which is a synchronous serial communication interface used for connecting digital devices together. The 1-bit signal from the ΣΔ-ADC is converted through a decimation process and a low pass filter into a standard 16-bit-signed PCM (Pulse Code Modulation) signal with a sampling frequency rate of 6.66 kHz. The PCM signal carries on the information of the vibrations to be measured. The amplitude values range between $-2^{16-1}-1=-32767$ $\text{Decimal}_{16\text{-bit-signed}}$ and $+(2^{16-1}-1)=+32767$ $\text{Decimal}_{16\text{-bit-signed}}$, where the digit unit is a signed 16-bit sequence converted into a decimal number.

3.2 Digital MEMS microphone

The test microphone, shown in figure 1b is a *STMicroelectronics*, Model *MP34DT05-DS* [19], which is a top-port, ultra-compact, low-power, omnidirectional, digital MEMS microphone built with a capacitive sensing element and an IC interface. It consists of a condenser microphone sensor (1.3 mm diaphragm) which converts the acoustic signal into an electrical one, and an application-specific-integrated-circuit (ASIC) which is necessary for signal processing. It is composed of a power supply, an amplifier and an analogue-to-digital converter. Power supply and clock are supplied by an external controller (STM 32F769I Discovery [20]). The latter acquires the digital signal and is programmed to provide the MEMS microphone a clock of 3 MHz and a voltage of 3.5 V. The microphone signal is sampled with a frequency of 48 kHz and acquired using an I^2S protocol that converts the PDM signal (Pulse Density Modulation) in a 16-bit-signed PCM (Pulse Code Modulation) signal, with amplitude values ranging from $-2^{16-1}=-32768$ $\text{Decimal}_{16\text{-bit-signed}}$ to $2^{16-1}-1=+32767$ $\text{Decimal}_{16\text{-bit-signed}}$, where the Decimal unit is a signed 16-bit sequence converted into a decimal number.

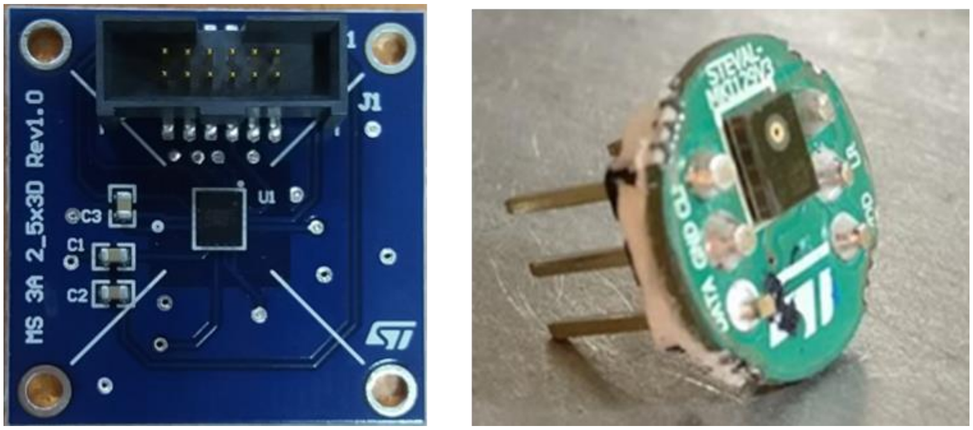

Figure 1: a) Digital MEMS accelerometer (board 25 mm×25 mm); b) Digital MEMS microphone diameter (diameter of the board 12.8 mm). All sensing elements and electronic components are included within the "black-small-box" within the board (volume of about 10 mm^3).

4. Traceability of digital sensor

Since current standards do not provide specific methods for the calibration of MEMS accelerometers and microphones, especially for digital sensors, the existing standard calibration procedure by comparison with a reference transducer (ISO 16063-21 for accelerometers [21] and IEC 61094-5 for microphones [22]) are re-adapted and realized by INRiM. As a matter of facts, «these technologies have different mounting requirements, use different testing and calibration protocols, and use digital interfaces for data and communications» [11]. Expanded uncertainties, at a confidence level of 95%, were evaluated according to GUM [23].

4.1 Calibration of digital MEMS accelerometer

The calibration set-up here proposed, consisting of a single-axis vibrating table on which aluminum inclined planes are screwed, allows to generate a projection of the reference acceleration along three axes simultaneously. A single vertical sinusoidal acceleration at nearly-constant amplitude acts as reference acceleration a_{ref} along the vertical of the system. In this way, accelerations of proportional amplitudes released along the three axes, are simultaneously generated on the inclined surface plane. From simple trigonometrical laws, the reference accelerations detected by the digital MEMS accelerometer, along its three sensitive axes, are expected to be:

$$a_x = \left| a_{ref} \sin(\alpha) \cos(\omega) \right| \tag{4}$$

$$a_y = \left| a_{ref} \sin(\alpha) \sin(\omega) \right| \tag{5}$$

$$a_z = \left| a_{ref} \cos(\alpha) \right| \tag{6}$$

where, α is the inclination angle, ω is the angle of rotation, a_{ref} is the Root Mean Square (RMS) reference acceleration along the vertical axis of the system.

By considering the 3-axis accelerometer, the calibration procedure can be applied for 3 outputs simultaneously, by evaluating both main and traverse sensitivities. Each acceleration component a_j (j=1, 3), in $m \cdot s^{-2}$, can be expressed as a linear combination of the 3-axis digital MEMS accelerometer outputs U_i (i=1, 3), in $D_{16\text{-bit}}$, as shown in following equations:

$$a_j = \sum_{i=1}^{3} U_i \cdot A_{i,j} \tag{7}$$

Or in general matrix form:

$$\mathbf{a} = \mathbf{U}\,\mathbf{A} \tag{8}$$

By taking into account the so-called exploitation matrix $\mathbf{A = [U^TU]^{-1}U^Ta}$, in order to evaluate sensitivity matrix, considering the linearly independent sets of values, each 3-axis digital MEMS accelerometer output U_i (i=1, 3) can be expressed as a linear combination of the acceleration components a_j (j=1, 3), according to the following equation: $\mathbf{U} = \mathbf{a}\,\mathbf{A}^{-1} = \mathbf{a}\,\mathbf{S}$, where $\mathbf{S}$ (3×3) is the sensitivity matrix, in which the diagonal terms are the main sensitivities, and the out-of-diagonal terms are the transverse sensitivities. Sensitivity matrix can be calculated as the inverse of the exploitation matrix, $\mathbf{S}=\mathbf{A}^{-1}$.

Calibration is carried out at 11 frequencies between 5 Hz and 3 kHz and in static condition. A reference acceleration at nearly-constant amplitude of 10 m s^{-2} is generated along the vertical axis of the system. The calibration set-up is shown in figure 2a; the main terms of sensitivity values are reported in the graph of figure 2b.

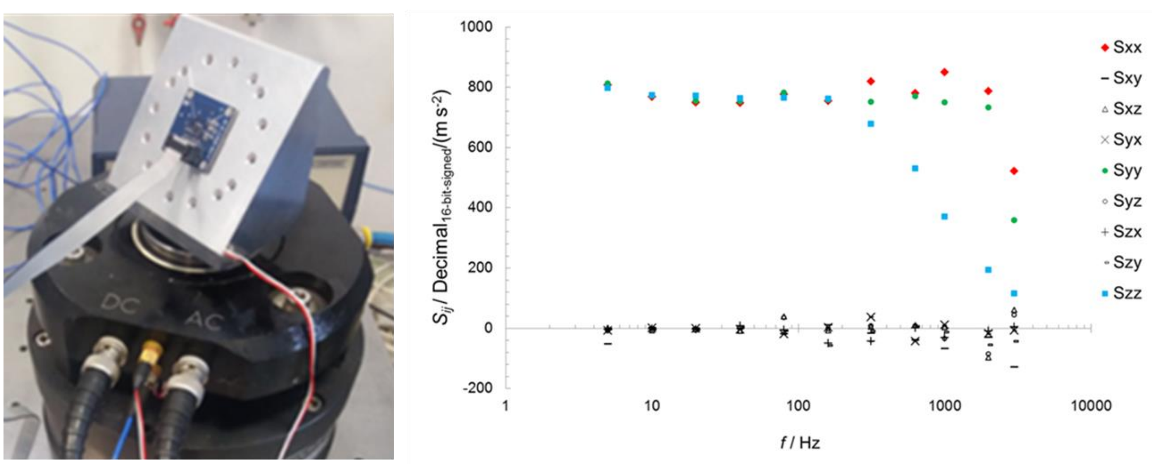

Figure 2: a) The calibration set-up: the MEMS fixed to the inclined plane on the vibrating table. b) Sensitivity matrix terms S_{ij} evaluated at an amplitude of about 10 m s^{-2} as a function of frequency.

4.2 Calibration of digital MEMS microphone

The principle of the comparison method here proposed is that when the reference microphone and the test microphone are exposed to the same sound pressure simultaneously, the sensitivity of the test microphone can be calculated from the sensitivity of the reference microphone. The definition of the pressure sensitivity assumes that the sound pressure over the diaphragm is uniformly applied. To guarantee that the two microphones are exposed to the same sound pressure, it is necessary that the two microphones, without protection grid, are positioned face-to-face with parallel front surfaces separated by approximately 1 mm in either a coupler or a jig and that a radially symmetric sound source is positioned coaxially with the microphones axis. Since in active couplers there is an increasing potential for non-uniform sound pressure distributions at high frequencies due to different geometric sizes of the two microphone membranes and to air leakages, it is suggested that the microphones are mounted in a jig, i.e. a device that holds the two microphones in an open space (face-to-face, with a small gap between them) with an additional sound source used to generate the sound field (Barham et al., 2014).

For this reason, measurements were carried out in the hemi-anechoic room of INRiM (350 m^3), in order to have a low background noise (around 17 dBA) and a large open space. The sound pressure was generated by a closed-box loudspeaker (6-inch-diameter speaker placed in a box of 0.51×0.40×0.40 m^3), coaxially aligned with the axis of symmetry of the two microphones at a distance of 30 cm and at a height of 105 cm from the floor. For the evaluation of the sensitivity and frequency response, stationary pure tones from 20 Hz to 20 kHz were generated at sound pressure levels between 85 dB and 100 dB, at one-third (from 20 Hz to 1 kHz), one-sixth (from 1 kHz to 6 kHz) and one-twelfth (from 6 kHz to 20 kHz) octave band steps, in order to have a higher resolution at high frequencies and accurately evaluate diffraction effects. Measurements were carried out in two configurations (L_{12} and L_{21}), obtained exchanging the two microphones, in order to minimize diffraction effects which are particularly significant at higher frequencies. Moreover, for each configuration, the MEMS microphone was rotated four times by 90°, in order to evaluate the measurement reproducibility, which takes into account uncertainties due to the different sizes and positions of the two microphone membranes. Measurement setup is shown in figure 3a and calibration results in figure 3b.

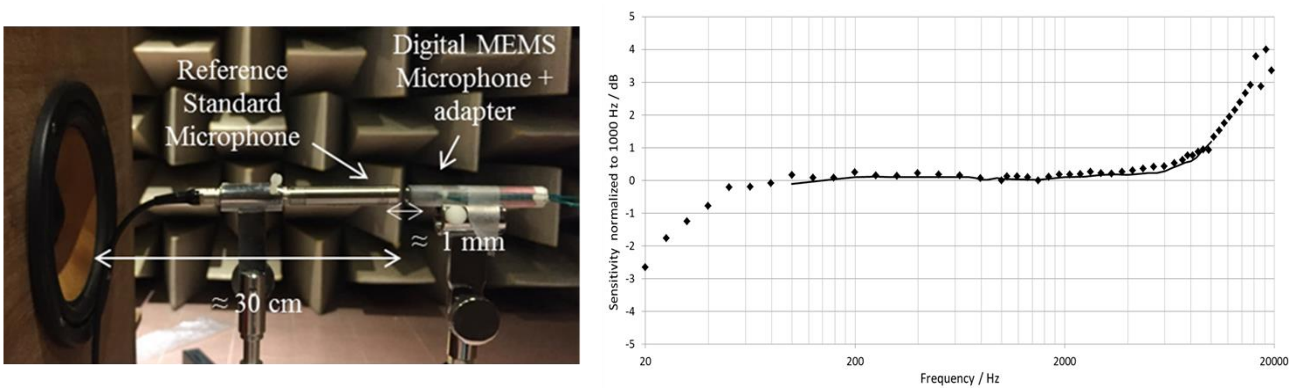

Figure 2: a) The calibration setup in the hemi anechoic room. b) Sensitivity $S_{dgz,dB}$ of the digital MEMS microphone as a function of frequency f, along with the expanded uncertainties (at a confidence level of 95%), at sound pressure levels between 85 dB and 100 dB.

5. Conclusions

In this paper, two innovative systems are presented for the calibration of digital MEMS accelerometers and microphones realized and *mise-en-pratique* at INRIM. The systems allow to perform calibrations by comparison with a reference transducer. A suitable «digitized» sensitivity is also defined. These experimental investigations represent a first attempt to provide metrological traceability to digital MEMS sensors for vibration measurements and acoustic measurements. The metrological traceability is of fundamental importance, at present, both for the development of this technology in the field of science and measurement techniques and for its application in different technological and industrial areas.

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