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# METROLOGICAL CHARACTERIZATION OF DIGITAL MEMS ACCELEROMETERS IN DYNAMIC CONDITIONS: AN INVESTIGATION OF LINEARITY IN AMPLITUDE AND TEMPERATURE EFFECTS

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**Abstract:**
In several applications, such as industrial plants monitoring, or peculiar manufacturing process, the sensors are subjected to a wide range of acceleration amplitude levels or shocks, as well as thermal changes, that could affect the micro electro-mechanical inner parts, altering their performance and reliability. In this work, by applying a calibration procedure developed at INRIM, the main sensitivity of digital MEMS accelerometers is evaluated, as a function of amplitude, in the frequency domain. Moreover, a survey of temperature drift, from -20 °C up to 80 °C, is also performed, to characterize the suitability of digital MEMS accelerometers for actual applications.

**Keywords:** digital MEMS accelerometer; calibration; amplitude; thermal effects

## 1. INTRODUCTION

In the field of applied metrology in vibrations, a growing interest aimed at investigating the linearity of the accelerometers' response, not only in the frequency range but also in amplitude, has been observed [1], [2]. In particular, it is important to verify the linearity of the amplitude response, within the full-scale acceleration ranges, for different amplitudes of excitation, since the actual deviation from linearity is generally unknown.

This emerging need is addressed also to digital MEMS/NEMS accelerometers, although, at the present day, calibration of MEMS sensors with digital output is still a challenge in metrology of dynamic accelerations and vibrations. On the other hand, digital MEMS/NEMS accelerometers, as components of large sensor-networks, are nowadays widely used for monitoring and survey, in many applications, in which high precision is an essential requirement to supply high-quality data, within the due trustworthiness [3], [4].

In this work, by applying a suitable calibration procedure recently developed at INRIM [5], the main sensitivity of six digital MEMS accelerometers is evaluated (along a single axis), as a function of amplitude response, namely at 1 m/s$^2$, 3 m/s$^2$, 10 m/s$^2$ and 20 m/s$^2$ (between $\pm 2\,g$ up to $\pm 16\,g$, according to the full-scale of MEMS sensor) and as a function of frequency, namely at 10 Hz, 100 Hz and 1 kHz. The measurements of the linearity in amplitude are carried out by comparison with a reference accelerometer (according to the ISO Standard 16063-21). Moreover, a qualitative survey of temperature drift, within a range of environmental conditions from -20 °C up to 80 °C, is also performed, to characterize the suitability of digital MEMS accelerometers for actual applications [6].

## 2. MATERIALS AND METHOD

The amplitude-dependence and the thermal effects on the calibration of six nominally identical low-power digital 3-axis MEMS accelerometers (ST, model LSM6DSR [7]), are investigated. The device is composed of an accelerometer sensor, a charge amplifier, and an analog-to-digital converter. The digital MEMS accelerometers are connected by a serial cable to a separated external microcontroller, in which other electronic components are integrated. In this analysis the same external microcontroller (ST, model 32F769IDISCOVERY [8]), to acquire the digital samples and to provide the required power supply to the MEMS accelerometer, is used. Sensor and microcontroller are depicted in Figure 1.

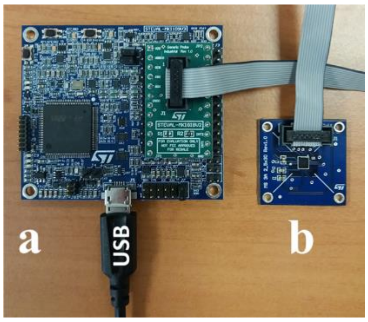


Figure 1: a) Microcontroller; b) MEMS sensor

The calibration procedure and the related metrological characterization of the six MEMS sensors are aimed at verifying the actual response in the frequency domain, as a function of amplitude and thermal conditions, along the *z*-axis. The procedure is based on a calibration by comparison, with a reference accelerometer (in analogy to ISO Standard 16063-21 [9]). In Figure 2 the calibration set-up is shown. To avoid further sources of uncertainty, the calibration of the six MEMS is performed by using the same external microcontroller, although its influence in terms of systematic errors and uncertainty contribution, is negligible.

Figure 2: Calibration set-up by comparison with a reference accelerometer (PCB model 080A199/482A23), mounted below a supporting table, at INRIM.

## 3. EXPERIMENTAL RESULTS

As a preliminary observation, as recently pointed out by the authors in previous works [10], calibration sensitivity data (determined according to ISO Standard 16063-21, with a suitable calibration systems realised at INRiM) of nominally identical MEMS (i.e., from a same large batch), show a certain dispersion. The six MEMS accelerometers, tested in this work, are a part of 100 identical MEMS accelerometers, calibrated at INRIM, as a function of frequency from 5 Hz up to 1 kHz. As observed, each single MEMS accelerometer is charcaterized by its own sensitivity values (and its own sampling rate [11]), distributed around the nominal value (provided by the manufacturer). In Figure 3 the actual variability of sensitivity values of 100 MEMS, for a single axis, is shown.

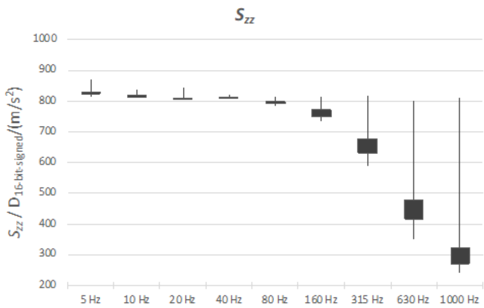


Figure 3: Sensitivities (with 4*g* full-scale) along *z*-axis of the 100 MEMS as function of frequency.

Values of traceable sensitivity are expressed in “decimals”, i.e., $\mathrm{D}_{16\text{-bit-signed}}/(\mathrm{m/s^2})$, instead in m*g*/LSB. Namely, 1 $\mathrm{D}_{16\text{-bit-signed}}/(\mathrm{m/s^2})$ corresponds to 1 $(\mathrm{m}g/\mathrm{LSB}\times(9.8065/1000))^{-1}$. It is worth noting that the nominal value declared by the manufacturer is 836 $\mathrm{D}_{16\text{-bit-signed}}/(\mathrm{m/s^2})$, i.e., 0.122 m*g*/LSB, regardless the frequency range, and without any indication of uncertainty. Namely, from experimental results of 100 calibrations, we obtained $840 \pm 15$ $\mathrm{D}_{16\text{-bit-signed}}/(\mathrm{m/s^2})$ at 10 Hz, $820 \pm 22$ $\mathrm{D}_{16\text{-bit-signed}}/(\mathrm{m/s^2})$ at 100 Hz and 329 $\mathrm{D}_{16\text{-bit-signed}}/(\mathrm{m/s^2})$ at 1 kHz with a strong asymmetric distribution, by using a full-scale of $\pm 4\,g$, with a reference acceleration amplitude of 1 m/s$^2$.

As shown, the sensitivity values along *z*-axis range between 869 $\mathrm{D}_{16\text{-bit-signed}}/(\mathrm{m/s^2})$ at 5 Hz down to 239 $\mathrm{D}_{16\text{-bit-signed}}/(\mathrm{m/s^2})$ at 1 kHz. Moreover, the distributions of sensitivity data show asymmetric distribution, instead normal distribution, with different degrees of asymmetry, as shown as an example in the graphs of Figure 4, Figure 5 and Figure 6, for the selected frequencies of 10 Hz, 100 Hz and 1 kHz.

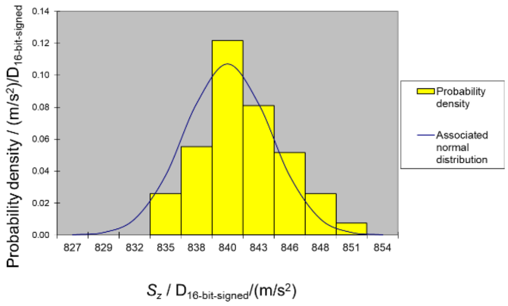


Figure 4: 100 MEMS quasi-symmetric distribution of sensitivities at 10 Hz, along *z*-axis.

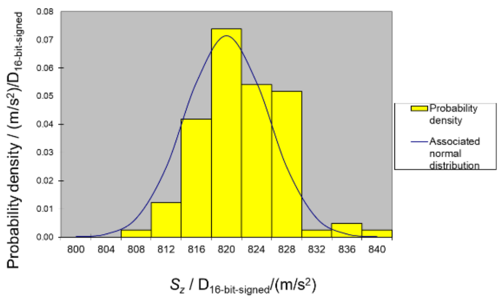


Figure 5: 100 MEMS asymmetric distribution of sensitivities at 100 Hz, along *z*-axis.

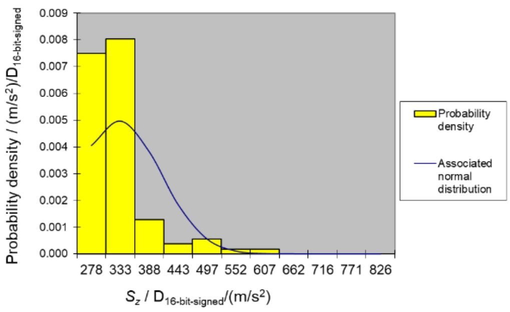


Figure 6: 100 MEMS strong asimmetric distribution of sensitivities at 1 kHz, along *z*-axis.

These asymmetric distributions of sensitivity values do not allow to univocally identify a nominal single value of sensitivity to be attributed to this type of MEMS sensor, basing on simple statistical approaches. As a first consequence in this work, we consider the sensitivity values, and the related variation due to amplitude, for each single MEMS sensor separately.

In Table 1, the actual values of sensitivity, at 10 Hz, 100 Hz and 1 kHz, with a reference acceleration of 10 m/s$^2$ (with a full-scale of 4 *g*) of the six MEMS here investigated are shown. Data are expressed as a mean value (among 3 repetitions) with the expanded uncertainty calculated as 2 $\sigma$.

Table 1: Sensitivity values, espressed in $D_{16\text{-bit-signed}}/(\text{m/s}^2)$), with calibration repeteability uncertainty, of the six MEMS investigated.

| MEMS | 10 Hz | 100 Hz | 1 kHz |
|---|---|---|---|
| #1 | 832 ± 4 | 841 ± 2 | 354 ± 2 |
| #2 | 832 ± 4 | 825 ± 2 | 246 ± 2 |
| #3 | 833 ± 2 | 827 ± 2 | 272 ± 2 |
| #4 | 831 ± 4 | 833 ± 2 | 309 ± 2 |
| #5 | 832 ± 2 | 833 ± 2 | 281 ± 2 |
| #6 | 831 ± 4 | 822 ± 2 | 238 ± 2 |

### 3.1. Amplitude calibration

Calibration is performed on a single axis as a function of different amplitudes of excitation. Three repetitions of measurements are carried out by varying the amplitudes of acceleration (1, 3, 10 and 20 m/s$^2$) and frequencies (10, 100, 1000 Hz). Depending on the generated acceleration amplitude, MEMS full scale is set to ± 2 *g*, ± 4 *g*, ± 8 *g*, and ± 16 *g*. By way of example, in the graph of Figure 7, the sensitivity values (MEMS #2) determined at 1 m/s$^2$, as a function of frequency and for different full-scale, are shown.

The sensitivity values, as previously shown in Figure 3, are almost constant from 10 Hz up to 100 Hz, and decrese up to 1 kHz.

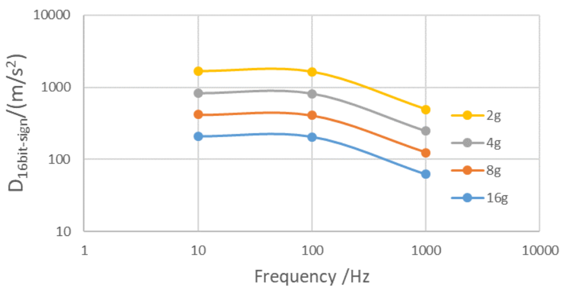


Figure 7: Sensitivity as a function of frequency at different full-scales.

In the following graphs of Figure 8, Figure 9 and Figure 10, as an example with a full-scale of 4 *g*, the experimental results of sensitivity as a function of different amplitudes at 10 Hz, 100 Hz, 1 kHz, are shown.

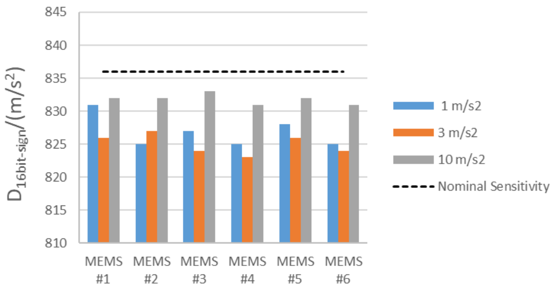


Figure 8: Sensitivity at 10 Hz (4 *g*).

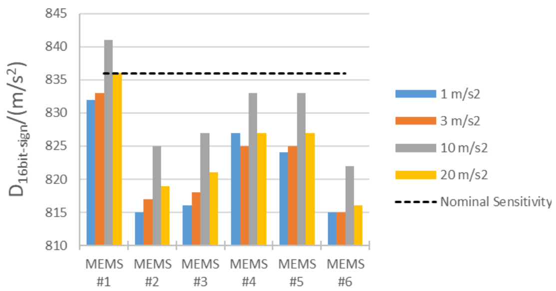


Figure 9: Sensitivity at 100 Hz (4 *g*).

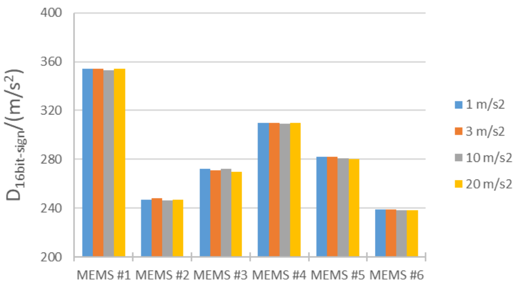


Figure 10: Sensitivity at 1 kHz (4 *g*).

In the graph of Figure 11 the sensitivity data of the six MEMS, are compared as a function of different amplitude, at 100 Hz (4 *g* full scale). It is worth noting that, although "absolute" values of sensitivity are different, the trend with respect amplitude is strongly similar, among the six MEMS.

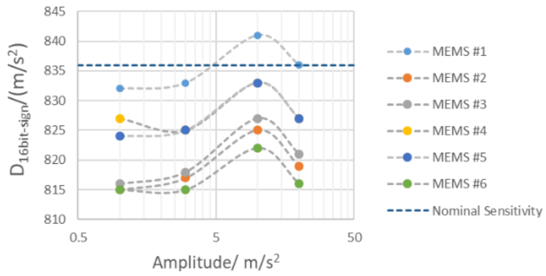


Figure 11: Trends of sensitivity values at 100 Hz (4*g*), as a function of amplitude acceleration.

### 3.2. Thermal effects

A preliminary investigation is carried out performing calibration (on a single axis) as a function of the environmental temperature. From the data-sheet of the manufacturer the linear acceleration sensitivity changes vs. temperature (from -40 °C to +85 °C) of ±0 .01 %/°C. Calibration is carried out at 160 Hz, with 10 m/s$^2$ of amplitude, in a proper climatic chamber. As shown in Figure 3, the sensitivity, at 160 Hz, is 761 ± 36 $D_{16\text{-bit-}}$

signed/(m/s$^2$). The temperature ranges from -20 °C up to 80 °C (with a stable R.H. at 40 %). Measurements as a function of temperature are performed in the accredited laboratory of CENTROTECNICA, Masate, by comparison with an accelerometer KISTLER (mod. 8705A50M1), fixed outside, on an thermal-insulating fixture. Both the MEMS sensor and the microcontroller are located in the climatic cell, since it is supposed that both components could be close in actual environmental applications, as shown in Figure 12.

Figure 12: Experimental set-up for calibration by comparison in temperature controlled conditions.

Inside the climatic cell the temperature of the air and the temperature of the supporting base is simultaneously monitored. In Figure 13 the preliminary results determined on MEMS #1 are depicted. The observed stability allows to confirm the manufacturer's specification.

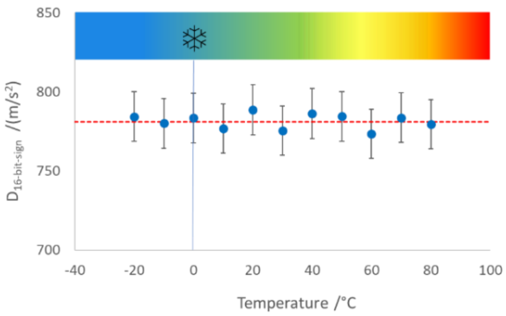


Figure 13: Temperature effects on the sensitivity value of MEMS #1.

## 4. CONCLUSIONS IN BRIEF

As observed, althought each single MEMS is characterized by a specific sensitivity (frequency dependent) lying within an asymmetric distribution, generally below the nominal value provided by the manufacturer, the responses as a function of different amplitudes of acceleration, are very similar among the six MEMS. Variations of sensitivity, as a function of amplitude, are below 2 % - 3 % from 1 m/s$^2$ up to 20 m/s$^2$, in the frequency range from 10 Hz up to 1 kHz, for all full-scale. Also thermal effects do not affect the sensitivity values of the MEMS sensor investigated, in the environmental temperature range, from -20 °C up to 80 °C. The investigation made it possible to verify the stability of the MEMS response as a function of the acceleration amplitude, and as a function of temperature.

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