A contribution to trustworthiness of data from digital MEMS accelerometers for smart mobility

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***Abstract* – In this work the problem of traceability of sensors used for intelligent mobility is addressed, in particular with reference to MEMS digital accelerometers. This topic is of great importance from the point of view of data reliability, and has significant implications in the field of safety. For this purpose, a rotating calibration bench is used to reproduce the conditions of use in the field, and the results are compared with calibration data obtained on linear type benches.**

Keywords – Trustworthiness, Traceability, Calibration, MEMS Accelerometer, Digital Sensor.

I. INTRODUCTION

Smart digital sensors installed on vehicles, together with sensing systems integrated into road infrastructure, make possible the realization of what is called "smart mobility", which comprises several approaches and technologies, including advanced driver assistance systems, autonomous vehicles, smart lighting, traffic and speed control [1, 2]. By acquiring data of different types, and exchanging information in real time (communication vehicle to infrastructure, vehicle to vehicle, vehicle to cloud storage, vehicle to pedestrians, vehicles to other entities [1]), these systems can improve road safety, reduce transit times, improve road usability, reduce environmental impacts and increase energy savings.

The possibility of realizing such types of systems is strongly linked to that of using miniaturized sensors and devices. For instance, NEMS accelerometers see application in the automotive field i.e., for crash air-bag deployment systems in automobiles [3].

A critical aspect of smart and sustainable mobility is the reliability of data provided by the sensors installed in cars and surrounding road infrastructures [4]. In fact, since all smart mobility applications are based on the use of measurement data, the functionality and security of the services depend on the reliability of the provided information, particularly in cases where incorrect data can seriously affect people's safety. This is especially true in the case of autonomous vehicles, which are seen as the future of the automotive field, but whose development and commercialization still have to face significant safety challenges [5]. In addition, the trustworthiness of data provided by sensors is also a fundamental requirement for legal vehicle roadworthiness and insurance liability [6].

The metrological traceability, "whereby the measurement result can be related to a reference through a documented unbroken chain of calibrations, each contributing to the measurement uncertainty" (VIM - Vocabulaire International de Métrologie), is the first response to the request for reliability of measurement data [7,8]. It allows to guarantee the quality of data provided, with information on sensitivity, uncertainty, confidence levels, supplied by established calibration procedures involving the use of certified samples.

However, building the credibility of sensor data that can be used to support smart mobility, particularly for digital three-axis MEMS accelerometers that are often used on vehicles [9], is an achievement that is not trivial for several reasons. Sensors based on nanotechnologies are also promising but their development still appears to be in its dawn [10-12].

First of all, the calibration must be substantially revisited with respect to the procedures established for traditional accelerometers: the current calibration procedures (e.g. ISO 16063-21) do not contemplate three-axis accelerometers, in which, in addition to the main sensitivities, also the transversal ones can be significant, due to not perfect perpendicularity of the sensor axes [13-15]. Furthermore, these calibration procedures were not developed for sensors that use digital interfaces and whose output is expressed in digital units [16].

The dynamic response is often not studied [17], also because adequate calibration systems and methods for three-axis digital MEMS accelerometers are not yet available. On the other hand, the calibration of these sensors, which have a very low unit cost, requires procedures and benches characterized by the same strong reduction in costs, and this excludes the possibility of using expensive systems such as, for example, tri-axial shakers.

In this scenario, measurement instrumentation manufacturers are currently the almost exclusive source of information about the metrological characteristics of digital sensors, but standardized calibration techniques are not currently available, which can ensure traceability and evaluation of uncertainty according to accredited procedures. Therefore, in the case of three-axis MEMS digital accelerometers, the sensitivity is generally assessed by the manufacturer using non-traceable methods, sometimes without declaration of the uncertainty. In cases in which the uncertainty is reported, it is estimated under static conditions, and without distinguishing among x-, y-, and z-axis, which necessarily present different characteristics for construction reasons [16].

In a previous work, the authors evaluated main and transverse sensitivities of 25 digital MEMS accelerometers, through an inter-laboratory comparison [16], using two different methods from the point of view of the calibration test bench (however linear in both cases) and of the data processing method. The results of the two laboratories were statistically compatible.

In this work, the authors intend to calibrate an accelerometer of the type already examined, making use of a rotating calibration bench, to simulate the way of use of accelerometers in the field, where the different axes can be subjected to different accelerations not only in module, but also in frequency, due to the combined effect of centripetal and tangential accelerations. The results obtained with this different calibration approach will be compared with those obtained in the previous work, to get helpful information regarding the most advantageous testing techniques for digital and 3-axial MEMS accelerometers to be used for smart mobility.

This work aims to be a first preliminary step towards the construction of a common metrological framework to ensure the data trustworthiness of road and automotive sensing systems. Moreover, it sets the attention and aims at paving the ground for the identification of methods for the characterization of sensors based on nanotechnologies, in accordance with the current development trends.

II. MATERIALS AND METHODS

The three-axis digital MEMS sensors examined in this work (Fig. 1) are low-power accelerometers that are part of an IMU (Inertial Measurement Unit) from STMicroelectronics, model LSM6DSR. The digital MEMS accelerometers are connected via a serial cable to a separate external microcontroller (STMicroelectronics, model STEVAL MKIGIBV2), acquiring digital samples and communicating with the PC via the USB port.

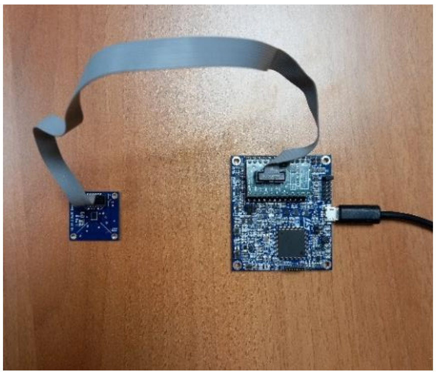
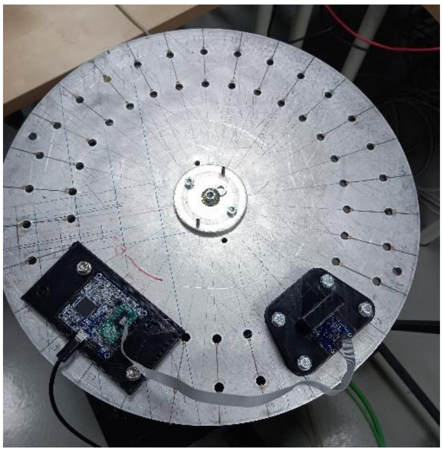


Fig. 1 MEMS accelerometer under test and IC board.

a)



b)

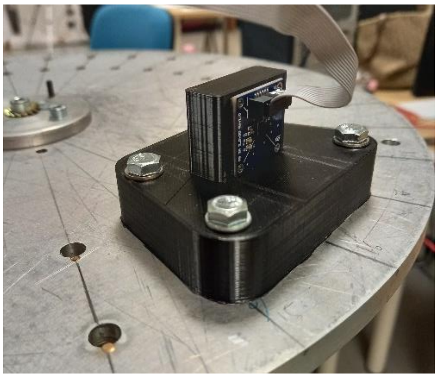


Fig. 2 Rotating calibration bench: a) Aluminium disk and supports for the MEMS sensor and the microcontroller; b) Detail of the sensor placed in one of the possible positions on the support (tangential y-axis, radial z-axis, vertical x-axis).

The accelerometers are positioned through a PLA (Polylactic Acid) support on the rotating aluminium disk (Fig. 2.a). In addition to the support for the accelerometer, another one for the microcontroller has also been provided, as seen in Fig. 2.a, to avoid short circuits.

The PLA support for the accelerometer has been necessary to physically separate it from the metal disk, since the electromagnetic field produced by the motor interferes with sensor functioning, inhibiting data acquisition when placed at direct contact with the disk itself.

This support permits the positioning of the sensor in different ways, which allows the stress of the three axes in a radial, tangential or vertical position: one of these ways is shown in Fig. 2.b, where the y-axis is tangential, the z-axis is radial, and the x-axis is vertical.

A preliminary characterization of the bench has been carried out using a triangulation laser sensor (model optoNCDT 1420, Micro-Epsilon, reproducibility 0.5 µm, linearity 8 µm) (Fig. 3).

Fig. 3 Displacement sensor for the characterization of the test bench.

In particular, the disk has been divided into thirty sectors, and a displacement measurement in the vertical direction has been carried out on each of them, during one complete rotation, at three different distances from the edge (5 mm, 20 mm, 50 mm) to highlight any irregularities.

The sensor has been tested by subjecting the disk to an oscillation with an amplitude of 30° and a frequency of 3Hz, according to a sinusoidal law.

The reference signal is obtained from the encoder output. In particular, the reference tangential acceleration a_t, the reference radial acceleration a_r and the reference vertical acceleration a_v, for each sensor position, are defined by equations (1), (2) and (3), where $\omega(t)$ is the instantaneous angular velocity, f is the oscillation frequency, r is the distance of the sensing element of the accelerometer with respect to the rotation axis, and g is the acceleration due to gravity [16].

$$a_t = 2 \cdot \pi \cdot f \cdot \omega(t) \cdot r \quad (1)$$

$$a_r = \omega^2(t) \cdot r \quad (2)$$

$$a_v = g \quad (3)$$

$\omega(t)$ is provided at a frequency of 1 kHz by the PLC connected to the servo motor.

It should be noted that the determination of the reference accelerations requires the preliminary evaluation of the radius r, i.e. the distance of the sensitive element of the accelerometer from the axis of rotation.

This evaluation can be done by positioning the sensor at different distances, starting from an initial radius, r (the unknown quantity), and increasing this distance by a known amount Δr.

The relationship between the sensor output, y, and the increment Δr of the distance from the initial value, r, can be obtained through a least squares regression, using a linear model [16]:

$$y = m \cdot \Delta r + b \quad (4)$$

The value of the radius is obtained from the ratio $r = b/m$.

In the present work, the configuration of the bench made it possible to realize only two radial positions for each axis, therefore, the simple determination of the straight line through two points has been applied. In the final configuration, the bench will be structured to account for different radial positions and thus allow a more accurate evaluation of the radius.

To assess the sensitivity, the method used in this preliminary evaluation consists in determining the FFT peak of the signal coming from the accelerometer to be calibrated and that of the reference signal: the ratio of the two quantities indicates the sensitivity value.

The evaluation has been made on the signal coming from the axis placed in the tangential direction, for which the FFT peak corresponds, theoretically, to the oscillation frequency of 3 Hz. In fact, in the radial direction, the signal amplitude does not allow to obtain satisfactory signal-to-noise ratios. In a subsequent phase of bench redesign and optimal setting of the test parameters, the radial direction will also be considered to fully exploit the investigation potential of the calibration method, also from the point of view of the cross-talk assessment.

III. RESULTS

In the first test campaign, the accelerometers were calibrated using two different linear benches, one from Univaq and one from INRiM. The calibration data of 25 MEMS accelerometers of the described type at 3 Hz, 6 Hz, and 10 Hz, and amplitude of 1 m/s^2, provided by the two laboratories, demonstrated compatible results in terms of main and transverse sensitivity, with relative extended uncertainties between 2% and 6%. On average, a main sensitivity of 1657 ± 71 $D_{16\text{-bit-signed}/(m/s^2)}$ for the x-axis, 1653 ± 72 $D_{16\text{-bit-signed}/(m/s^2}$ for the y-axis, and 1668 ± 50 $D_{16\text{-bit-signed}/(m/s^2)}$ for the z-axis were obtained, against a sensitivity declared by the manufacturer of 1671 $D_{16\text{-bit-signed}/(m/s^2)}$ [16].

No significant differences were identified between the sensitivities of the 25 MEMS, when axes and frequencies examined were equal, while an effect of the axis and the vibration frequency was recognized [16].

As far as the rotating bench is concerned, the results of the characterization show irregularities, due to imperfect planarity and perpendicularity of the disk with respect to the axis of rotation, highlighted in Fig. 4. In the graph of Fig. 4 it can be also noted the presence of a plateaux in correspondence of the sectors n° 15-16-17, in correspondence of which the accelerometer support has been, therefore, positioned.

The measurement carried out at the three different distances from the edge showed the presence of an inclination of the disk towards the rotation axis of about 0.5°, which has been taken into account in the evaluation of the uncertainty, as will be clarified in the following.

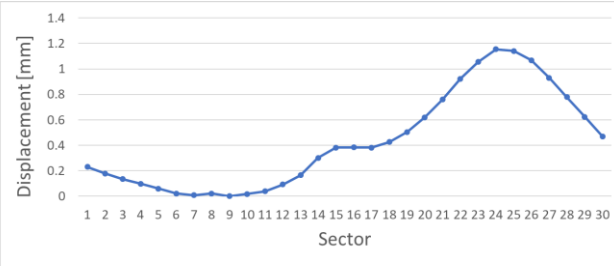


Fig. 4 Displacement measured in the vertical direction, 50 mm from the edge of the disc, during one complete rotation.

In the case of the rotating calibration bench analysed in the present work, as explained in the methodological section, the output signals from the MEMS accelerometer under analysis have been compared with the signals obtained from the encoder, after appropriate processing as indicated in the equations (1) and (2), to obtain the tangential and radial reference acceleration, respectively (Fig. 5).

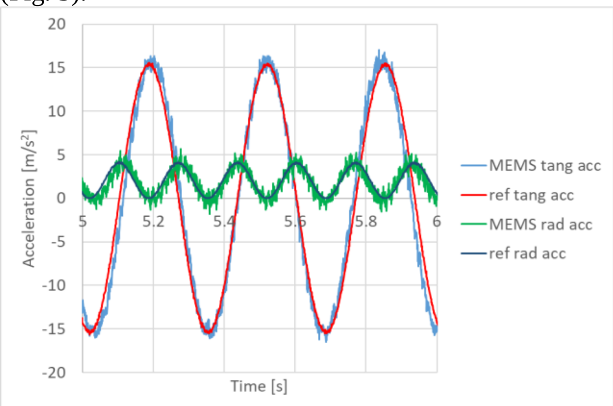


Fig. 5 Comparison between MEMS output acceleration and reference acceleration ("MEMS" and "ref", respectively, in the legend), in the tangential and radial direction ("tang" and "rad", respectively, in the legend).

In the preliminary tests carried out for this work, the results in terms of main sensitivity, determined as described in Section 2, are equal to 1666 $D_{16\text{-bit-signed}/(m/s^2)}$ for the x-axis, 1688 $D_{16\text{-bit-signed}/(m/s^2)}$ for the y-axis, 1681 $D_{16\text{-bit-signed}/(m/s^2)}$ for the z-axis, with repeatability below 0.5% in all cases. These results appear to be compatible with those obtained in tests on linear slides.

Concerning the uncertainty due to the determination of the radius, a standard deviation of 0.2 mm has been evaluated, which corresponds to a percentage contribution of ~ 0.2% on a radius r = 125 mm. This contribution is reflected identically on the reference acceleration.

The characterization of the bench in the area swept by the accelerometer showed a maximum angle of inclination of the disk of 0.5°, also considering imbalances due to vibrations. This angle produces a component of the acceleration of gravity on the axis in a radial position, which is reflected in a contribution on the sensitivity of 0.4% in terms of standard deviation.

The experimental results have also highlighted a variability in the sampling frequency of the MEMS accelerometer, and an average value of the frequency itself that does not correspond to the set one of 1660 Hz. This behaviour was already detected in the previous measurement campaign [19].

This sampling frequency variability produces a piecewise phase shift between the sensor output signal and the reference signal, when the nominal frequency of 1660 Hz is assumed.

For the accelerometer under examination, in particular, the average sampling frequency is 1617 Hz, corresponding with a peak of the FFT centred on 3 Hz (except for the resolution).

This issue requires attention and will be deepened in the continuation of the work with reference to the following main points:

1. it is necessary to evaluate how much the variability of the sampling frequency affects the uncertainty of determining the sensitivity with the FFT peak method, used in this work;
2. the variability of the sampling frequency does not allow the application of some methods of evaluation of the main and transversal sensitivities in which a point-to-point comparison with the reference accelerations is expected [18]. It is therefore necessary to develop specific methods to deal with this problem properly.
3. for the developed methods it will be necessary to evaluate the contribution of uncertainty due to the variability of the sampling frequency.

IV. CONCLUSIONS

In this work, preliminary evaluations have been carried out on the sensitivity of MEMS-type digital accelerometers, determined by resorting to a rotating calibration bench.

The results obtained (1666 $D_{16\text{-bit-signed}/(m/s^2)}$ for the x-axis, 1688 $D_{16\text{-bit-signed}/(m/s^2)}$ for the y-axis, 1681 $D_{16\text{-bit-signed}/(m/s^2)}$ for the z-axis) are compatible with the values previously determined on linear slides, when on 25 accelerometers of the type analysed, an average sensitivity of 1657 ± 71 $D_{16\text{-bit-signed}/(m/s^2)}$ for the x-axis, 1653 ± 72 $D_{16\text{-bit-signed}/(m/s^2)}$ for the y-axis, and 1668 ± 50 $D_{16\text{-bit-signed}/(m/s^2)}$ for the z-axis, resulted [16].

Repeatability was less than 0.5% for all three axes.

The other main uncertainty contributions, due to the determination of the radius and the irregularities of the bench, have been evaluated: they are, respectively, of the order of 0.2% and 0.4% in terms of standard deviation.

These contributions can be reduced by redesigning the bench in an optimized way in the continuation of the work.

An important aspect that has been highlighted concerns the sampling frequency of the accelerometer which is not constant and, on average, lower than the nominal one. This problem requires the development of specific methods for the evaluation of main and transverse sensitivities, and the assessment of the related uncertainty, which will also be the subject of future work.

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