Identification of calibration and operating limits of a low-cost embedded system with MEMS accelerometer

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Abstract. In this paper some aspects concerning the calibration uncertainty of three-axis low-cost accelerometers for possible use in diagnostics of civil buildings are considered, using a linear slide and a laser vibrometer as the reference.

In order to analyse the principal and cross sensitivity and the offset of the sensor in dynamic conditions, the sensitivity matrix method has been used.

Some considerations about the operating limits of a low-cost embedded system with MEMS accelerometer have been discussed, with reference to the calibration procedure.

In particular, the effects of the non-constant sampling and of the achievable sampling rate, are studied with reference to the calibration uncertainty and to the capability of the calibration procedure to assess the best metrological performances of the system under test.

1. Introduction

Many applications can be found in different fields of engineering, where a network of a significant number of accelerometers, have to be used to monitor the system of interest. Only to cite some relevant examples, a distributed network of accelerometers for Structural Health Monitoring (SHM) of buildings and of civil infrastructures [1], for earthquake monitoring [2], for condition monitoring of high performance tool machines aiming to incipient fault location and classification.

Due to the mechanical complexity of the systems, in most real cases three-dimensional acceleration fields are of interest, therefore requiring a large number of three-axis accelerometers for monitoring and diagnosing purposes. In all these applications accuracy of measured data is obviously a mandatory requirement for reliable diagnosis, together with the need of low cost sensors.

Some solutions based on new sensor technologies (MEMS, FOS, ...), are available for low cost three-axis accelerometers and networking applications of accelerometers already exist for the above-mentioned applications [3], [4]. Today the trend is to design integrated solution systems with several sensors embedded on the same device, in particular low cost accelerometers.

Several low-cost solutions are available on the market [5], based on MEMS accelerometers with integrated ADC system. A new generation of microcontrollers allows us to communicate with these accelerometers with standardized serial buses (for instance FC). The controller is also very simple to code, as, for example, the Atmega328 controller belonging to the Arduino Uno system, programmed by means of a similar C++ language. Furthermore, this way integrated low cost and low power solutions to monitor accelerations are very simple to implement.

Some aspects have to be considered when such solutions are used, mainly affecting the measurement uncertainty of three axis sensors;

- cross sensitivity;
- frequency rate of data;
• phase control of data coming from different sensors.

In fact, even though many operating examples could be found, nevertheless, these technologies, need to be characterized with respect to many influencing factors, related to both environmental (temperature, humidity, time stability ….) and metrological aspects: in particular, cross sensitivity [6], [7], [8], [9]. Even though a great attention is paid to the indication of cross sensitivity performances by calibration of them, literature indications are often unsatisfactory for many reasons. Some works propose several methods to calibrate accelerometers in dynamic conditions and all are based on sensitivity matrix [6], [7], [8], [9], [10], [11], [12]. Generally the calibration of the embedded solutions is based on non-standard procedures like the mean of data acquired in static conditions [13] or in the best cases is limited to the auto-calibration procedure, available in the integrated accelerometer firmware [2], [14]. Typically, the reference for the auto-calibration procedure is the gravity acceleration. Anyway, in most real applications, the acceleration solicitations are effectively and contemporaneously operating on all the three-axis and mutual interaction between measuring axes should be taken into account accurately; these mutual interaction between axes are often neglected.

Using low cost microcontroller and communication solutions requires that special attention is devoted to both enhance the data rate and the synchronization of data deriving from different sensors especially when modal analyses of monitored structures are useful for the analysis to be carried on [15], [16].

Based on these considerations, this paper describes a procedure for accurate evaluation of operating limits of a low-cost embedded system based on MEMS accelerometer. The frequency range of acceleration is 0 to 10 Hz, realized by linear oscillation according a sinusoidal behavior.

In particular, measurement uncertainty will be evaluated, with reference to main and cross sensitivities, data rate, also in terms of time interval stability as for data acquisition. The effect of settings in terms of coding strategy of the microcontroller and of the transmitting of the data will be also taken into account.

The information gained from the calibration procedure will be used to also improve the settings of the embedded low-cost system, according to a recursive approach.

The effect of reference acceleration will be also studied in order to define a calibration test bench accurate and of reduced cost.

The paper is organized according to the following steps:

– in section 2 the methodology will be discussed, concerning the experimental solutions able to realize the requested reference acceleration and the procedures for data processing;

– in section 3 results of tests are presented which have been carried out according to the proposed methodology. The operating limits and the accuracy improvements of a low cost accelerometer system made by the calibration technique will be discussed. Particular attention will be paid to the reduction of cross sensitivity and to the improvement of the time stability of task times, for uncertainty reduction.

Conclusions end the paper.

2. Materials and methodology

A linear vibrational motion is realized by a linear slide according to a sinusoidal time; frequencies of oscillation in the range 0 to 10 Hz are operated by an actuator driven by the computer. An inclined steel plate is installed on the test bench; the inclination angle is of 45° with respect to the horizontal plane.

Two three-axis accelerometers can be placed on the plate of different characteristics; accurate positioning at different angles of rotation on the inclined plane (0°, 30°, 45° and 60°) with respect to an horizontal line can be realized by pre-machined holes (figure 1).

The velocity of the slide in the motion direction can be accurately monitored by a Laser Doppler Vibrometer, LDV (figure 2).
The low-cost system under test is based on Arduino Uno controller and a low-cost MEMS accelerometer (figure 3). Similar solutions are used in [2], [10], [13], [14], [17], [18], [19], [20], [21]. The Arduino Uno software was coded in a similar C++ language and the PC based acquisition software for all the system is coded in NI LabVIEW like the solutions proposed in [2], [19].

The comparing accelerometer is a Sequoia FastTracer, an accelerometer using MEMS technology that incorporates into sensors three-axes sensor technology and the capability of analog to digital conversion. Vibration data are exported directly to the computer via a standard USB port, turning it thanks to an application software.

The velocity signal of the LDV is acquired with a NI c-Rio system coded with Labview RT. The results are synchronized and elaborated in Matlab.
For the general calibration of the sensor the following relationship between the input accelerations and output signals can be set:

\[
\begin{pmatrix}
V_x \\
V_y \\
V_z
\end{pmatrix} =
\begin{pmatrix}
S_{xx} & S_{xy} & S_{xz} \\
S_{yx} & S_{yy} & S_{yz} \\
S_{zx} & S_{zy} & S_{zz}
\end{pmatrix}
\begin{pmatrix}
a_x \\
a_y \\
a_z
\end{pmatrix} +
\begin{pmatrix}
q_x \\
q_y \\
q_z
\end{pmatrix}
\]

(1)

where:

- \( V = (V_i) \): output array,
- \( A = (a_i) \): reference accelerations array,
- \( S = (S_{ij}) \): sensitivity matrix,
- \( Q = (q_i) \): offset array.

A total of 12 parameters have to be evaluated; a linear Least Squares Optimization will be used to estimate them, as described in references [2], [6] and [7].

It is to be pointed out that this procedure is the most complete approach; in fact, taking into account the possibility of not negligible offset vector means that predefined hypotheses are not considered.

The output from the LDV is a velocity signal and it must be processed to get information about the acceleration. In particular, the velocity signal has to be differentiated and its components, according to the axes of the accelerometer in calibration, should be evaluated. Moreover, the appropriate component of the gravity acceleration \( g \) has to be added to each direction.

**Figure 3.** Low cost system based on Arduino Uno controller and an accelerometer ADXL 350Z Eval board.

**Figure 4.** Angle of rotation of the accelerometer on the inclined plate.

Then, if the rotation angle on the inclined plate of the accelerometer is indicated as \( \alpha \) (figure 4), the accelerations along the three axes can be obtained as follows:

\[
a_x = a_{vib} \cdot \cos (45^\circ) \cdot \cos (\alpha) + g \cdot \cos (45^\circ) \cdot \cos (\alpha)
\]

(1)

\[
a_y = -a_{vib} \cdot \cos (45^\circ) \cdot \sin (\alpha) - g \cdot \cos (45^\circ) \cdot \sin (\alpha)
\]

(2)
\[ a_z = a_{vib} \cdot \cos (45°) - g \cdot \cos (45°) \]  

(3)

where \( g \) is the gravity acceleration, and \( a_{vib} \) is the acceleration in the motion direction, by differentiating the LDV output.

In order to reduce the numerical noise in acceleration signal from the LDV, the velocity derivative has been computed by the following formula:

\[ a_{vib} = \omega \cdot v_{vib} \]  

(4)

being \( \omega \) the pulsation of the sinusoidal motion and \( v_{vib} \) the measured velocity by the LDV.

The stability of the LDV signal has been evaluated on the base of 30 cycles, as a standard deviation of peaks values, and it is equal to 0.12% of the amplitude.

The LDV has been used as a reference sensor and the two considered acceleration measuring systems, both based on MEMS sensors (the low-cost MEMS and the Sequoia Fast Tracer) have been calibrated with reference to it, in order to highlight the differences.

3. Results of dynamic calibrations and comparison between sensors

The Sequoia accelerometer has been calibrated with reference to the LDV signal.

The Sequoia and the LDV signal have been acquired at a sampling rate of 1024 Hz.

Considering the observations made in previous paragraphs, the accelerometer behavior during a whole oscillation period is considered in comparison with the reference; the test is repeated at different positions of the sensor; for each position the reference accelerations along the x, y and z axes have been calculated, depending on gravity and motion acceleration components and compared with the corresponding outputs of sensors in all directions.

In order to evaluate the variability of the results, 10 different sets of points have been considered, corresponding to different oscillation periods; 10 different matrices \( S \) and offsets \( q \) have been correspondingly calculated.

Then, the average matrix \( S \) and the average offset vector \( q \) have been calculated:

\[
S = \begin{pmatrix}
0.99 & 0.010 & 0.0033 \\
-0.030 & 1.0 & 0.022 \\
0.011 & 0.0033 & 1.0
\end{pmatrix}
\]

\[
q = \begin{pmatrix}
0.16 \\
0.34 \\
0.073
\end{pmatrix}
\]

and also the standard deviations of them (called dev.st(S) and dev.st(q), respectively) have been calculated:

\[
\text{dev.st}(S) = \begin{pmatrix}
0.0019 & 0.0015 & 0.0017 \\
0.0019 & 0.0012 & 0.0026 \\
0.0024 & 0.0021 & 0.0016
\end{pmatrix}
\]

\[
\text{dev.st}(q) = \begin{pmatrix}
0.027 \\
0.031 \\
0.031
\end{pmatrix}
\]

As can be seen, a maximum relative deviation from the mean values of 0.19% has been evaluated for the coefficients of the main sensitivities, that is a negligible variability.

Considering all causes of uncertainty, these results are in a close agreement with the values on the calibration certificate of the sensor.
Also for the low-cost system, the sensitivity matrix $S'$ and the offset vector $q'$ have been calculated on the basis of the reference values, as an average of 10 different matrices and offsets:

$$
S' = \begin{pmatrix}
1.1 & 0.012 & 0.019 \\
0.044 & 0.98 & 0.069 \\
-0.0047 & -0.012 & 0.98
\end{pmatrix}
$$

$$
q' = \begin{pmatrix}
-0.16 \\
-0.74 \\
-0.73
\end{pmatrix}
$$

and the standard deviations of them (called $\text{dev.st}(S')$ and $\text{dev.st}(q')$, respectively) have been calculated:

$$
\text{dev.st}(S') = \begin{pmatrix}
0.021 & 0.012 & 0.017 \\
0.021 & 0.011 & 0.018 \\
0.026 & 0.013 & 0.023
\end{pmatrix}
$$

$$
\text{dev.st}(q') = \begin{pmatrix}
0.26 \\
0.27 \\
0.32
\end{pmatrix}
$$

Also for low-cost acceleration measuring system the calibration matrix values are according the specification data, if the main sensitivities are evaluated and the cross sensitivity is evaluated as the mean of the matrix data.

The effect of the correction on the raw data of the MEMS accelerometer, by the matrix $S$ and the offset vector $q$ obtained, is shown in figure 5, and appears to be satisfying.

A maximum relative deviation from the mean values of 2.3% has been evaluated for the coefficients of the main sensitivities.

These results confirm that the methodology provides good results.

However, the calibration of the low-cost MEMS accelerometer with reference to the LDV signal, has involved some operational difficulties in applying the methodology and special attention.

The main problems are as in the following:

- the acquisition rate for the low-cost system is not perfectly constant over time;
- a reduced acquisition data rate has to be set, in order to guarantee safe data flow.

Both these aspects increase the variability of results and, therefore, the calibration uncertainty.

In fact, due to variability of the acquisition frequency of data of the low cost acceleration system, there is not time synchronicity between reference system and the one under calibration; this time jitter worsen variability of the results to be processed in order to evaluate the sensitivity matrix.

Furthermore, it is not possible to set an acquisition rate in the order of 1024 Hz, as for the reference, because an average frequency in the order of 200 Hz is the maximum limit beyond which the low-cost measuring system on the whole does not guarantee the reliability of the acquired values. That limit depends, of course, also on the controller and on the acquisition software.

This requires the calculation of the average acquisition rate of the sensor and the setting of the acquisition rate of the reference at that value.

The average acquisition rate of the accelerometer has to be evaluated on the time interval considered for the calibration, because otherwise large synchronization errors with respect to reference data may occur, making calibration results meaningless.

The described calibration procedure highlight the effects of some operating aspects of the low-cost measuring system; in fact, making the data rate high and stable, as much as possible, do not only affect the calibration uncertainty of the system, and this could be considered obvious, but also makes the calibration procedure easy, quick and effective, allowing to better define the system metrological performances.
4. Conclusions

In this paper some aspects concerning the calibration uncertainty of three-axis low-cost accelerometers for possible use in diagnostics of civil buildings are considered.

The test bench allows to realize a three-axis acceleration with enough accuracy to show the cross sensitivity and bias effects.

In order to analyze the principal and cross sensitivity and the offset of the sensor in dynamic conditions, the sensitivity matrix method has been used.

A LDV has been used to calibrate an embedded system with low-cost three-axis accelerometer in order to reduce the bias of the sensor and calculate the uncertainty of the system.

Some considerations about the operating limits of a low-cost embedded system with MEMS accelerometer have been discussed.

In particular, some problems in the application of the methodology to the low-cost system have been highlighted: the non-constant sampling, which requires the estimation of an average sampling rate, and the low sampling rate, which requires increasing the acquisition time.

These effects affect the uncertainty of calibration, and this could be considered obvious, but also preclude the calibration procedure to be easy, quick and effective, making difficult to define the best system metrological performances.

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