13th IMEKO TC10 Workshop on Technical Diagnostics
Advanced measurement tools in technical diagnostics for systems' reliability and safety
June 26-27, 2014, Warsaw, Poland

Distributed sensor network for structural characterization of buildings aggregates: discussion about aspects affecting measurement uncertainty

D'Emilia G.[1], Gaspari A.[1], Natale E.[1]

[1] *Department of Industrial and Information Engineering and Economics*
(University of L'Aquila, L'Aquila 67100 via G. Gronchi 18, phone +39 0862434324, fax +39 0862434303,
e-mail {giulio.demilia, emanuela.natale}@univaq.it, antonella.gaspari@graduate.univaq.it)

Abstract- In order to set integrated procedures involving geotechnical and structural aspects finalized to buildings diagnostics, uncertainty aspects are discussed concerning three-axis accelerometers and inclinometers for a distributed sensor network, allowing us to operate in a selective manner and preferring the most critical situations. Main topics to be considered for the uncertainty evaluation of measurements and of information to be used for building diagnostics are discussed. As a first step of the whole procedure of uncertainty evaluation, particular attention is dedicated to the calibration of sensors to be used, taking into account the requirement of simple and inexpensive solutions for both sensors and test benches. Experimental results show that satisfactory calibration accuracy could be achieved, also for the low frequency range, 0 to 10 Hz, but it strongly depends on the motion positioning with respect to the vertical axis, on the imposed motion law and, finally, on the parameter used as the reference. Requirements to be satisfied by the sensor are also analysed.

I. Introduction

Social safety and building heritage along with the sustainable urban development are important issues in setting strategic priorities in European operational framework. To this end, evaluating the condition and performance of existing civil infrastructure is a crucial aspect that allows decision-makers to configure the best activity lines, in generic words, aiming people life-quality improvement [1].

This challenge reasonably embraces the efforts coming from different disciplines in order to create a suitable informative database and recognize preventive measures of risk mitigation. Some perspectives involved are those of in situ inspection and investigation about mechanical properties of materials [2], or, for example, the characterization of the ground response for earthquake engineering applications [3]. In addition, depending on the purpose, one may move from a large-scale assessment of buildings [4], otherwise analyse structural and dynamic properties referring on an individual building [5], or conduct the analysis on a part of it, such as staircases relating to the whole structure [6].

On behalf of having integrated procedures involving geotechnical and structural aspects finalized to buildings diagnostics, a distributed sensor network is needed allowing us to operate in a selective manner and preferring the most critical situation. The newness lies in the simultaneous monitoring of ground and building structure and on the further transfer of the so-built information towards assessment procedures of the structural criticalities. That surely implies the need of a greater number of measuring sensors, for both vibration and inclination measurements, together with the need of different installation and processing techniques for the structure and the ground, but it seems to be promising from a point of view of the information capacity.

This newness, together with the will of covering wide areas in regard to different buildings by this multi-sensors network, sets the requirement of lower-cost solutions able to ensure the requested uncertainty of measurements anyway.

In fact, in decision making procedures the usefulness of information given by measurements strongly depends on their uncertainty, if the approach according to the product and process conformity check [7] is taken into account; therefore uncertainty evaluation plays a fundamental role with respect to the efficaciousness of the whole methodology.

Due to different reasons, achieving an adequate level of uncertainty is not a trivial result because of many factors:

- different quantities to be measured (acceleration, tilting, mechanical properties of soil,…),
- different type of buildings to be modelled for monitoring purposes,
- the need of using low cost measuring apparatuses in most of the measuring points,

- the time stability of instrumentation during the monitoring period,
- the great amount of experimental data to be acquired, processed and synthetized in order to get experimental indicators to be easily managed for decision about the intervention level,
- the need of integrating procedures and methodologies in a remarkably interdisciplinary context.

Taking into account all the uncertainty causes and their effects is obviously a process involving a long effort, but there are some aspects that could be considered “sine qua non” condition, in order to consider the process feasible. In particular a coherent approach is very promising, that is all the involved aspects should be considered as subsequent steps of the same knowledge process, that has to be faced in a integrated way from the beginning, (i.e. the sensors), to the end (i.e. data presentation, fusion, and synthesis).
In this paper, bearing in mind these considerations, the first aspect which is considered is the limit that could be achieved with reference to the uncertainty of sensors to be used for acceleration and inclination, taking also into account cost requirements.
This goal mainly involves sensor behaviour, its power supplying and conditioning and data acquisition technique, but also initial and periodical calibration; for this aim the methodology is presented in order to evaluate the calibration uncertainty of sensors for different quantities to be measured in this project.
Cost requirements as for the single measuring point and literature solutions [8], [9], [10] and the characteristics of the calibration test bench, designed for this specific application [11], [12], [13], [14], [15] will be taken into account. Preliminary results will be discussed with reference to the possibilities given by the integration of solutions to be taken, considering aspects connected to the sensor itself, to the conditioning and data processing aspects and, finally, to a calibration procedure tailored for this application.

II. Methodology

Calibration uncertainty of sensors will be evaluated with reference to the contribution of effects tied to both the calibration test rig and sensor characteristics, taking into consideration the simple and inexpensive solutions for sensing, sensor conditioning and data transfer modalities to the acquisition and processing system.
As for sensor uncertainty, repeatability, linearity, resolution and reference contributions will be considered.
When the test rig is considered, particular attention will be paid to the uniformity and stability of the values of acceleration to be realized.
Scientific evaluations, expert advice and market analysis led us to define the following ranges of interest for tests:

- frequency range: 0-80 Hz;
- maximum amplitude of vibration: ± 2g.

To calibrate the accelerometer chain, two different test benches have been used (Figure 1).
The calibration bench 1 has been used for sensor calibration in the frequency range 0 - 10 Hz.
The calibration bench 2 has been used for sensors calibration in the frequency range 10 - 80 Hz.
The bench 1 is based on a rotary device driven by a brushless servomotor, controlled through an angular encoder and a PLC, which allows us to realize different motion laws.

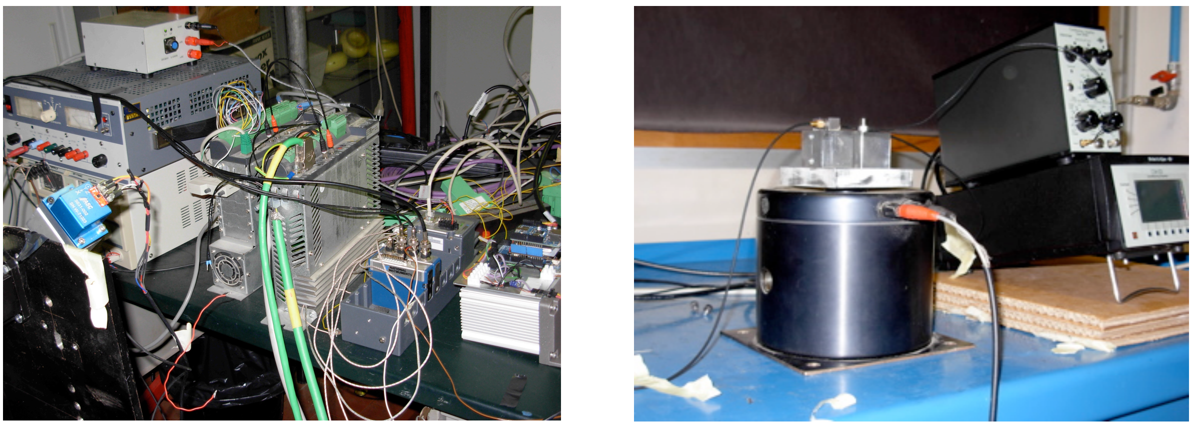
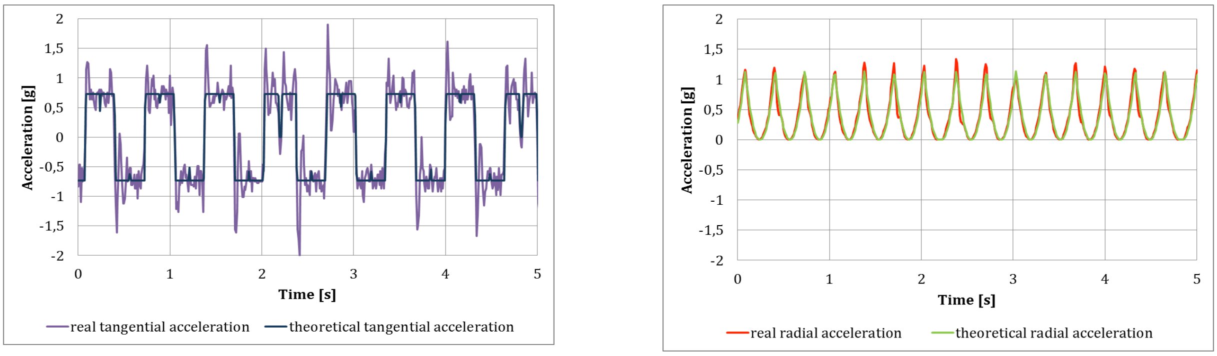


Figure 1. From left, respectively bench 1 and bench 2

The bench 2 is based on an electro-dynamic shaker which realizes a force of 50 N, in the frequency range 10 - 5000 Hz, driven by a high accuracy digital signal generator. The realized acceleration is single-axis and the behaviour of different axes of the sensors has been tested rotating the positioning of sensors.

High accuracy acceleration and inclination sensors will be used as a reference element, a three-axis accelerometer based on a capacitive MEMS technology on bench 1 and three high-quality single-axis piezoelectric accelerometers on bench 2.
Reaching satisfactory accuracy in the low frequency range requires to solve different problems with reference to the positioning of the motion, to the motion law and to the reference definition. As a first step, a saw-tooth temporal profile of the angular velocity, at different frequencies, has been realized. The rotation plan is vertical.
This velocity waveform produces a theoretical square wave as for tangential acceleration, that, through fundamental harmonic and higher-order harmonics, allows us to simultaneously check sensors behaviour at different frequencies, and it is easily programmable.
The tests have been carried out at constant spatial amplitude of vibration; therefore when the frequency is changed the acceleration amplitude changes too. This allows us to check both linearity and dynamic behavior.
The reference signal for tangential acceleration is obtained by twice differentiating the angular encoder signal which drives the servo-motor. The reference signal for radial acceleration is obtained according to the formula $\omega^2 \cdot r$, where r is the distance of the sensor from the centre of rotation and ω is the angular velocity. The amplitude of acceleration at different frequencies has been measured evaluating the FFT peak of the acceleration diagram for the frequency of interest. Repeated tests allowed us to evaluate repeatability for each motion condition.
The saw-tooth velocity motion law resulted unsatisfactory because of remarkable differences between theoretical and experimental motion law, as depicted in Figure 2. Theoretical acceleration is obtained through differentiation of the imposed saw-tooth velocity motion law, while real acceleration is obtained by twice differentiation of the angular encoder signal.



a) b)

Figure 2. Comparison between real and theoretical tangential (a) and radial (b) accelerations (fundamental component = 1,6 Hz).

In the second configuration the set motion law is sinusoidal and the rotation plan is horizontal in order to minimize the gravity effects. It is to be taken into account that this solution requires to adequately consider the cross-talking between axes because the realized motion is three-axial in therms of acceleration.
This configuration has been studied through the reference accelerometer in order to highlight the improvements in the motion law.

III. Results

In this section two classes of results will be presented: a comparison between two three-axis accelerometers aiming to put in evidence the effects of simple solution for conditioning electronics, interfacing and A/D conversion, on the metrological performance of sensor itself and a comparison between two solutions for test rig, as for the positioning of the motion with respect to the vertical direction, the motion law and the reference definition.

A. Comparison between sensors

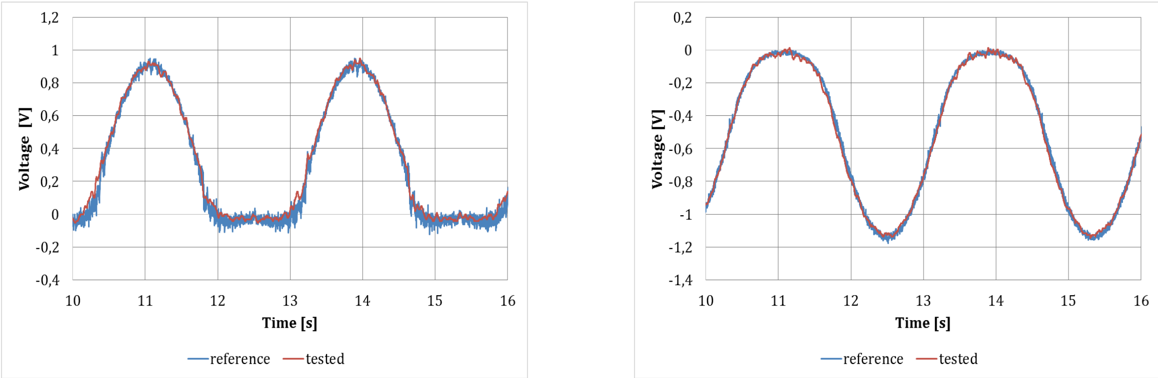
- Static test (0 Hz)

Sensitivity (V/g)			Standard Deviation (mV)		
	Reference Sensor	Low cost Sensor		Reference Sensor	Low cost Sensor
X-Axis	1,03	1,02	X-Axis	0,6	12,0
Y-Axis	0,97	0,99	Y-Axis	0,5	5,0
Z-Axis	0,99	0,97	Z-Axis	0,9	5,1

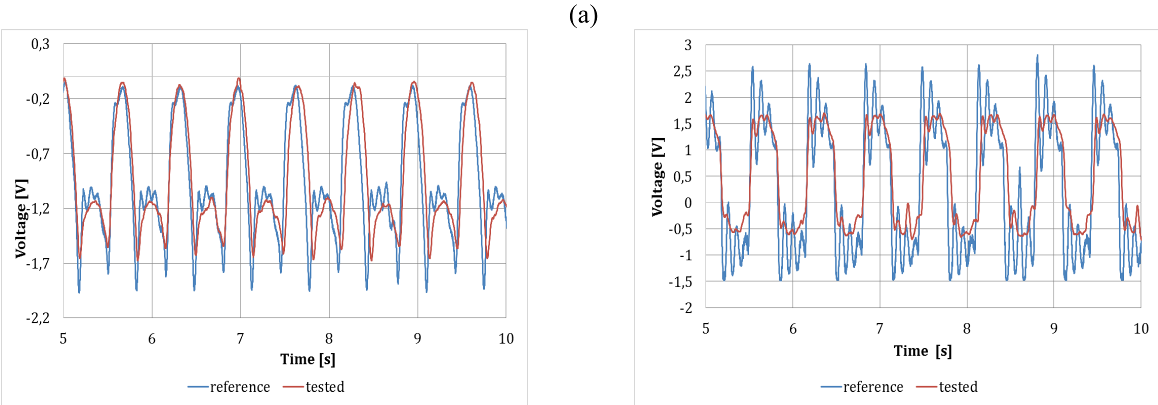
Table 1. Static sensitivity and standard deviation of tested accelerometers

- Low frequency behaviour (0-10 Hz)

Preliminary results are shown in diagrams of figure 2, showing comparison between reference and low cost sensor for different vibration frequencies in the range 0,3-1,6 Hz (fundamental component).



(a)



(b)

Figure 3. Comparison between reference and low cost accelerometers: 0,3Hz (a), 1,6Hz (b).
Left column: y-axis measuring. Right column: z-axis measuring

In particular when the tests are carried out at higher frequencies, the only reference accelerometer is able to reveal high frequency oscillations. The disturbing effects of gravity don't allow very accurate assessments of sensors.

Relative linearities of ±1% and of ±5% were found for reference and low cost sensors, respectively.

- High frequency behaviour (10-80Hz)

Repeatability and linearity of both sensors have been evaluated with reference to the envelope behaviour of spectra obtained by frequency sweeps in the range 10-80 Hz.

Figure 4 and Figure 5 show the comparison of behaviour of both sensors for repeated tests, at two levels of acceleration amplitude, 0,8g and 1,6g. The green dotted line refers to the averaged enveloped spectra for reference sensor. The differencies in terms of repeatability and linearity between the two sensors can be easily noted.

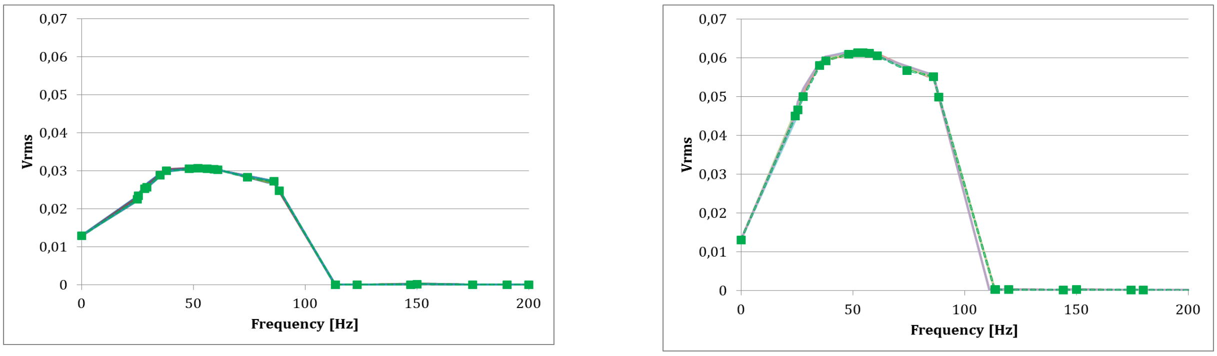


Figure 4. Repeatability and linearity check for reference sensor: 0,8g and 1,6g, respectively

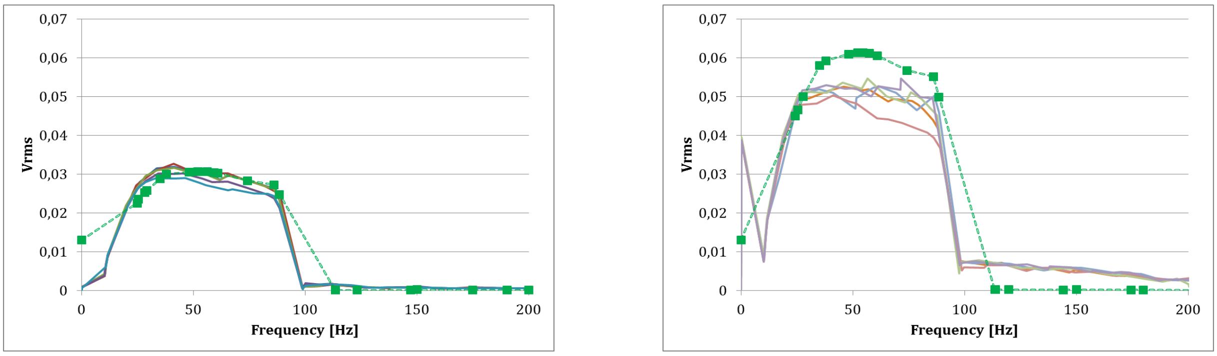
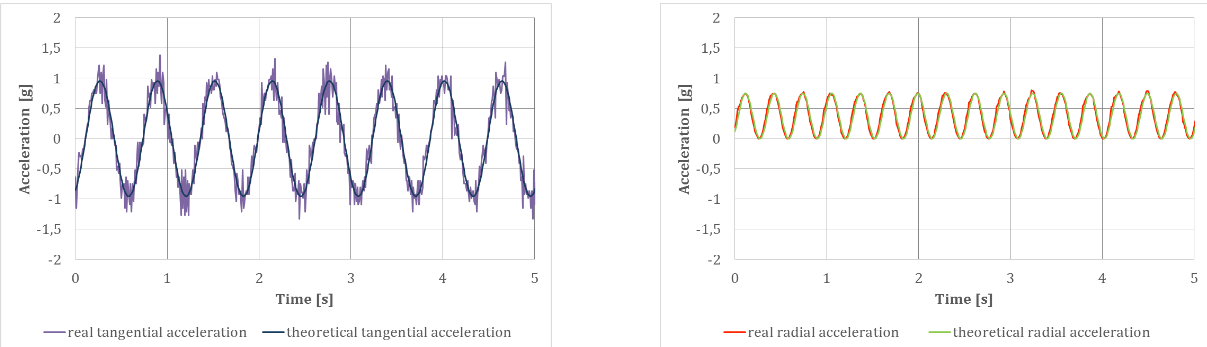


Figure 5. Repeatability and linearity check for low cost sensor: 0,8g and 1,6g, respectively

The above results show that satisfactory metrological performances are not easy to achieve with simple and low cost solutions, therefore further study is needed in order to reach the requested accuracy of data which are the starting point of the whole diagnostic methodology.

B. Comparison between test rigs

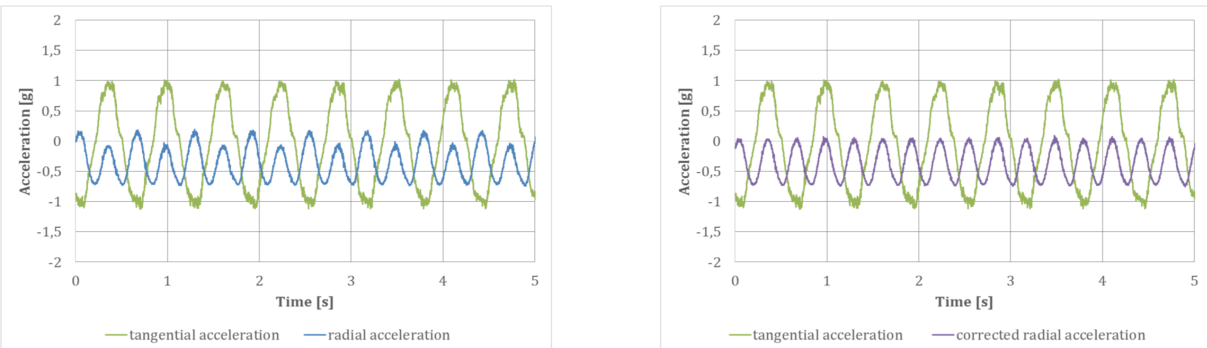
The improvement of the second configuration in respect of the first one in realizing a valid reference signal is remarkable, if data of Figure 2 and Figure 6 are compared. In Figure 6 theoretical acceleration is obtained by twice differentiation the imposed sinusoidal angular motion law, while real acceleration is obtained by twice differentiation of the angular encoder signal.



a) b)

Figure 6. Comparison between real and theoretical tangential (a) and radial (b) accelerations (fundamental component= 1,6 Hz)

The validity of reference signal also allow us to correctly taking into account the cross-sensitivity effects that could be easily corrected as it is shown in Figure 7.



a) b)

Figure 7. Comparison between measured tangential and radial accelerations before (a) and after (b) the cross-sensitivity correction

Conclusions

With the aim of facing step by step the analysis of uncertainty contributions of measurements to be used in the whole methodology involving geotechnical and structural aspects finalized to buildings diagnostics, some problems have been studied concerning the accuracy class of sensors and calibration procedures for accelerometers in the amplitude range ±2g and frequency range 0-80 Hz.
If the accuracy class of sensors is considered, the results show that satisfactory metrological performances are not easy to achieve with simple and low cost solutions with respect to commercial available acceleration transducers, therefore further study is needed in order to reach the requested accuracy of data which are the starting point of the whole diagnostic methodology.
With reference to the problems concerning the optimization of the calibration procedure and test bench, some interesting suggestions have been carried out, in particular considering vibrations in the low frequency range, concerning:

- Positioning of the rotation axis with respect to the vertical one;
- motion law;
- setting of the reference quantities.

The research will be carried on with the aim of being able to supply measurement data of satisfactory uncertainty. In particular, the stability of sensors to be implemented and the way for in field transfer of the measuring network will be also studied in the future.

References

[1] Wyss M., Rosset P., "Mapping seismic risk: the current crisis", *Nat. Haz*. vol. 68, pp. 49-52, 2013.
[2] Fiore A., Porco F., Uva G., Mezzina M., "On the dispersion of data collected by in situ diagnostic of the existing concrete", *Constr. Build. Mat,* vol. 47, pp. 208-217, 2013.
[3] Convertito V., Iervolino I., Zollo A., Manfredi G., "Prediction of response spectra via real-time earthquake measurements", *Soil Dyn. Earthq. Eng.*, vol. 28 pp. 492-505, 2008.
[4] Mansour A. K., Romdhane N. B., Boukadi N., "An inventory of buildings in the city of Tunis and an assessment of their vulnerability", *Bull Earthq. Eng.*, vol. 11, pp. 1563-1583, 2013.
[5] Rainieri C., Fabbroncino G., Verderame G. M., "Non-destructive characterization and dynamic identification of a modern heritage building for serviceability seismic analyses", *NTD&E Int.,* vol. 60, pp. 17-31, 2013.
[6] Sun H., Zhang A., Cao J., "Earthquake response analysis for stairs about frame structure", *Eng. Fail. Analysis*, vol. 33, pp. 490-496, 2013.
[7] EN ISO 14253-1:2013 Geometrical product specifications (GPS) - Inspection by measurement of workpieces and measuring equipment - Part 1: Decision rules for proving conformity or nonconformity with specification
[8] Zhao M., Xiong X., "A New MEMS Accelerometer Applied in Civil Engineering and its Calibration Test", *The Ninth International Conference on Electronic Measurement & Instruments*, vol. 2, pp. 122-125, 2009.
[9] Milligan D. J., Homeijer B. D., Walmsley R. G., "An ultra-low noise MEMS accelerometer for seismic imaging Sensors", *IEEE Sensors 2011 Conference*, pp. 1281-1284, 2011 .
[10] Vallet F., Marcou J., "A low-frequency optical accelerometer", *J. Opt.*, vol. 29, pp.152-155, 1998.
[11] Schiefer M. I., Bono R. "Improved low frequency accelerometer calibration" *XIX IMEKO World Congress Fundamental and Applied Metrology*, 2009.
[12] Choi K., Jang S., Kim Y., "Calibration of Inertial Measurement Units Using Pendulum Motion", *Int. J. Aeronaut. & Space Sci.*, vol. 11, pp. 234–239, 2010.
[13] Zhu C., Qin X., Wu Z., Zheng L., "Research on calibration for measuring vibration of low frequency", *International Conference on Mechanic Automation and Control Engineering*, pp. 3315 – 3318, 2010.
[14] Mohd-Yasin F., Nagel D. J., Ong D. S., Korman C. E., Chuah H. T., "Low frequency noise measurement and analysis of capacitive micro-accelerometers" *Microelectronic Engineering*, vol. 84, pp. 1788-1791, 2007.
[15] Ohm W., Wu L., Hanes P., Wong G. S. K., "Generation of low-frequency vibration using a cantilever beam for calibration of accelerometer", *Journal of Sound and Vibration*, vol. 289, pp. 192-209, 2006.