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SIMULTANEOUS 3-AXIS MEMS ACCELEROMETER PRIMARY CALIBRATION: DESCRIPTION OF THE TEST-RIG AND MEASUREMENTS

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Abstract − A procedure and a method for simultaneous 3-axis accelerometer primary calibration is presented. Nowadays, in the field of vibration monitoring, a relevant increase and diffusion of «low-cost» three-axial accelerometers (e.g. MEMS and NEMS) has been observed. The increased demand for calibration of MEMS and NEMS accelerometers and their inherent «low-accuracy», presupposes the opportunity to simplify the traditional calibration of triaxial accelerometers, as stated in Standard ISO 16063-21.

Keywords: primary calibration, vibration, triaxial MEMS/NEMS accelerometer

1. INTRODUCTION

Seismic and vibrational sensor networks, among others (such as thermal, visual, infrared, acoustic), are widely used in several field of monitoring. Sensor networks are involved in military applications, environmental applications, health applications, home applications, and other commercial applications [1].

The progress of micro/nano-electro-mechanical system (MEMS/NEMS) enables the application of wireless sensor networks (WSN) in the environmental monitoring field. MEMS and NEMS accelerometers, unlike traditional piezoelectric transducers, are generally characterized by medium/low-accuracy. However, in specific context of extensive applications (such as sensor networks), in which neither high accuracy nor detailed resolution on wide range of frequency and amplitude are needed, the technical performance of these accelerometers are considered adequate and satisfactory. Several examples of vibrational sensor networks, used to monitor sensitive infrastructure, have been recently developed.

In railway track security applications, since track breakage detection is prime concern of railways [2]. In bridges security monitoring, since scour on bridges usually damages piers and abutments, and is a major risk causing many bridge failures. Based on the MEMS technology, a wireless scour monitoring system is used to measure the scouring and deposition process due to variation of water levels at a bridge pier [3]. In offshore platform, in order to measure and monitor the vibrations of the structure; the sensor nodes are fixed and removed expediently, which saves the cost of signal line as well as installation time [4]. In industrial application, in nuclear power plants, petrochemical plants and many others application in which the early alert monitoring system is of a paramount importance [5, 6].

Nevertheless some lack in knowledge about calibration of this kind of sensors is recognized and the topic is still debated in metrological scientific community [7, 8], in particular in terms of reproducibility of experimental equipment performances.

An accurate metrological characterization of MEMS/NEMS accelerometers allows improving the accuracy and traceability of data collected by sensor networks. On the other hand, the classical calibration procedures (ISO Standard 16063-21 [9]) seem to be inadequate for two main reasons: excessively expensive (with respect of the sensors very low-cost) and highly accurate (with respect of sensors low accuracy).

In general terms, calibration procedure, as stated in [9], allows characterizing with great accuracy very sensitive sensors, while MEMS/NEMS accelerometers do not need high accuracy and resolution in calibration, but a defined traceability is needed as well. Nevertheless, it as to be said, a suitable calibration over a wide frequency range, (e.g. up to 500 Hz) allows to obtain a greater resolution and accuracy in measurement and evaluation at low frequency range (i.e. the typical frequency range of sensor networks working). In fact, whether sensors are calibrated at higher frequencies, it is possible to implement sensor networks more accurate, than sensor networks used only for control or survey (such as threshold level control, on-off alert …). Increasing the accuracy of a whole sensor network, allows to obtain higher resolution data, useful, as an example, in mechanical diagnostics, damage localization, wear and tear of machines, gears working survey and several other punctual monitoring. Moreover, promising accurate sensor networks, recently developed, allow to monitor cultural and artistic heritages, by using advanced acoustic and elastic emissions techniques, models and analysis [10, 14].

2. LITERATURE SURVEY

In the scientific and technical literature few methods or procedures are proposed in order to accurately calibrate simultaneously three axis accelerometers. As a matter of fact, stable and reproducible reference acceleration, i.e. the excitation system motion, is the main technical effort in the experimental procedure for simultaneous three-axial accelerometer calibration.

Researchers for the National Metrology Institute of Japan, in 2004, propose to use a very robust three-dimensional vibration generator [7], in which the motion on the system is servo-controlled along three axes simultaneously. Three-axis and three-dimensional water-cooled vibration generator are integer in a single "*shaker*". A pair of actuators is used for the horizontal motion generation by push–pull operation, along both *X*- and *Y*-axes. Original aim is to vibrate vertically as straight as possible

More recently, in the laboratories of the Department of Micro Engineering, Kyoto University, it has been developed an improved three-axis shaker [8] with measuring its three-axis rotation. For this experiment, a six-axis reference inertial sensor composed of three single-axis accelerometers and three single-axis gyroscopes was assembled.

In Italy, at the Department of Industrial Engineering, L'Aquila University, it has been design an innovative test-rig to calibrate simultaneously three-axis accelerometers [15]. For dynamic calibration a test bench based on a rotary device, driven by a brushless servomotor, controlled by a PLC by means of a high accuracy angular encoder is used.

All the systems are designed to perform simultaneous three-axis calibration, in general terms, at low frequencies, i.e. below 200 Hz.

3. CALIBRATION TEST-RIG

A simultaneous 3-axis primary calibration system, designed and realized at INRIM, is presented. The system, consisting of two separated vibrating tables on which is fixed a suitable inclined steel clamp (55°), allows to calibrate simultaneously the sensitivities along the three axes in a range of frequencies from 0 Hz (DC) to 1000 Hz and in range of amplitude between 0.02 m/s^2 and 50 m/s^2.

In Figure 1 is depicted the inclined steel clamp, on which the MEMS accelerometer is screwed, during calibration.

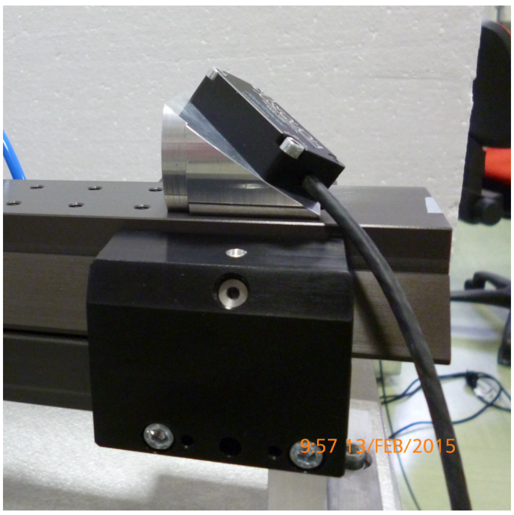

Fig. 1. The inclined steel clamp with the MEMS accelerometer during calibration.

The two tables allow to perform calibration at low frequency range from 40 Hz down to 0 Hz (DC) and at frequency up to 1 kHz.

The first system is equipped by a linear motor, able to perform motions both in vertical and horizontal position at low frequencies. The motion of the oscillating table is driven air cushion slides and the motion is controlled by an absolute encoder, with a maximum stroke of 200 mm peak to peak. The motion of the system is controlled by means a Michelson interferometer and laser doppler velocimeter. The system is depicted in Figure 1.

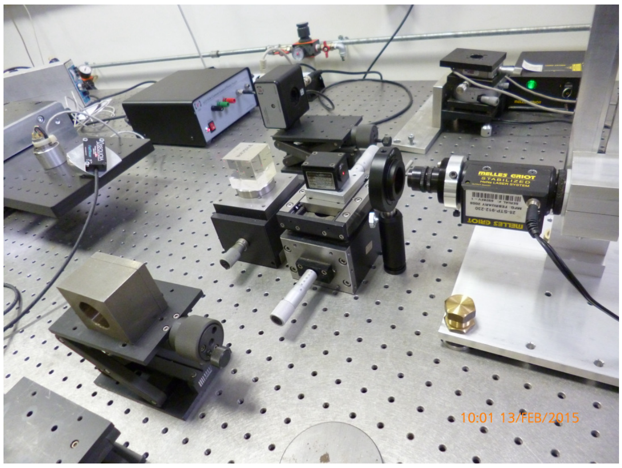

Fig. 2. Test-rig for simultaneously three-axis accelerometer calibration at low frequencies (0 Hz to 40 Hz).

The latter covers the frequency range between 20 Hz and 500 Hz (with the possibility to extend the frequency range up to 2 kHz). The oscillating table is driven by a shaker acting on the table binded on air cushion slides. Both oscillating tables support masses up to 5 kg.

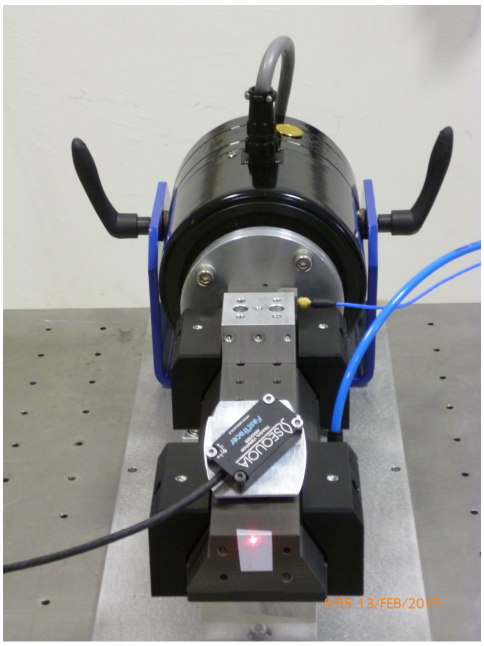

Fig. 3. Test-rig for simultaneously three-axis accelerometer calibration at higher frequencies (20 Hz up to 1000 Hz).

Transverse and rotational motions are evaluated by using an interferometric methods and laser Doppler velocimetry. In order to evaluate the resonances of the couplings a finite element model will be implemented.

The motion characteristics of the vibrating table (rotational motions and cross-motions) are determined and quantified by using interferometer analysis, while the accuracy of the displacement and velocity of vibration are determined by laser doppler vibrometer.

4. EXPERIMENTAL RESULTS

During calibration, the inclined steel clamp, on which MEMS accelerometer under test is screwed, induces transversal motions mainly due to its proper resonances and effects due to unbalanced masses. These effects, as it will be shown, become prevalent in particular at high frequencies. Moreover, since the MEMS accelerometer, as shown in Fig. 2 and Fig. 3, is fixed on the inclined steel clamp, with an angle of 55° (±0.1°) for Z-axis, and with the angle of 45°(±0.1°) for X-axis and Y-axis, on the plane of 55°(±0.1°), it is necessary to take into account the effects of sine and cosine angle dependence on the accuracy of the measured acceleration.

In order to quantify the actual differences between data measured on separate single axis and simultaneously on the three axis, a preliminary test has been carried out by testing a MEMS accelerometer, both a low and high frequencies.

In the low frequency range (0 Hz - 40 Hz), by using the test-rig depicted in Fig. 2, it has been observed that the procedure of simultaneous 3-axis calibration can be considered suitable and convenient, the main differences range within 2%, as depicted in the graph of Fig 4. Data show the measured percentage differences between acceleration measured by MEMS and the reference servo-accelerometer, fixed on the back of the table.

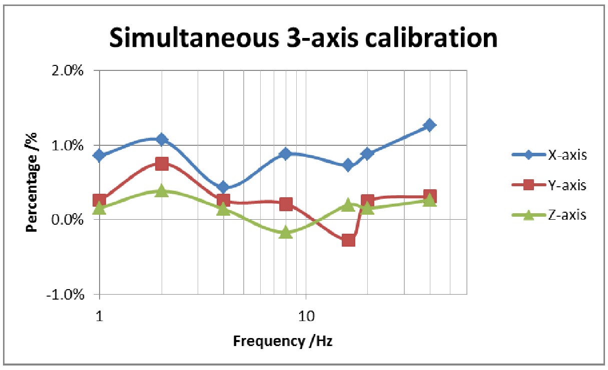

Fig. 4. Differences between MEMS and reference accelerometer during a single axis calibration.

The objective of this research is to extend the procedure suitability, at least within the 5% of accuracy, up to 1 kHz, in which "spurious" motions are relevant, in order to achieve a proper correction to the measured accelerations and related sensitivities. Actually, correction proposed must be referred to the system under investigation.

In the high frequency range (20 Hz - 1 kHz), traditional procedure of calibration (each single axis measured separately) and simultaneous 3-axis calibration show relevant differences. At first, it has been performed a comparison between the acceleration measured simultaneously by MEMS and by a reference accelerometer on the basis of transfer function, for each single axis. The differences measured , in percentage, are depicted in Fig. 5. It is possible to highlight the proper systematic deviation of the MEMS accelerometer under test.

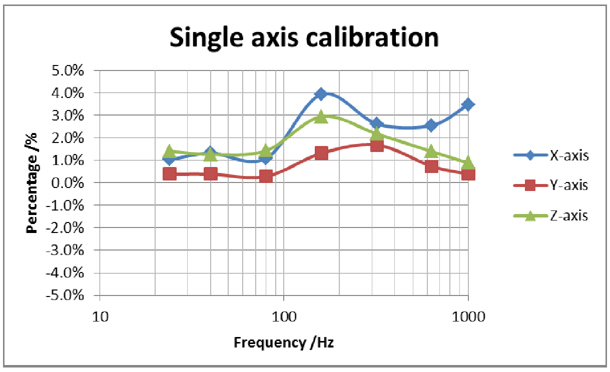

Fig. 5. Differences between MEMS and reference accelerometer during a single axis calibration.

Once verified the MEMS behavior, with the respect of traditional calibration, the effects due to the inclined steel clamp have been detected. As depicted in the graph of Fig. 6 the simultaneous 3-axis calibration shows relevant differences, in particular around 80 Hz and around 1st and 2nd natural harmonic at 160 Hz and 315 Hz.

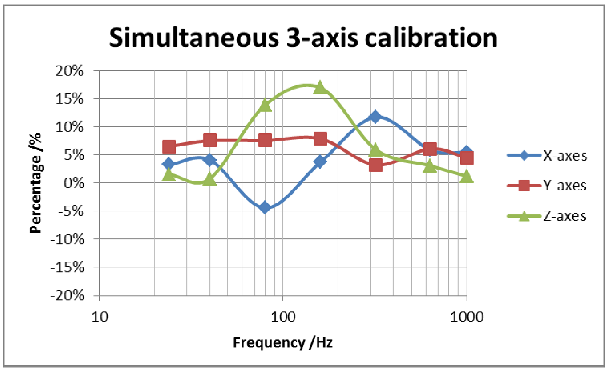

Fig. 6. Differences between MEMS and reference accelerometer during the simultaneous 3-axis calibration.

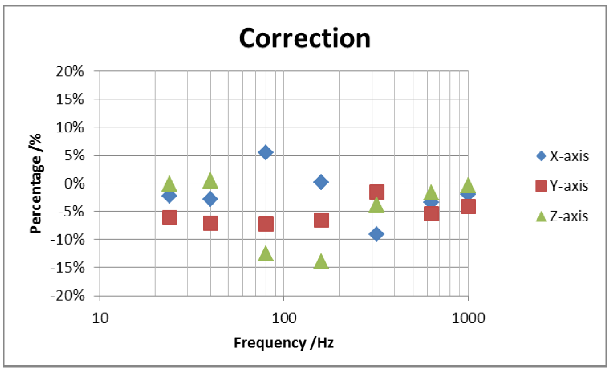

Fig. 7. Corrective terms calculated from the difference of single axis and simultaneous 3-axis calibration.

Once the difference between the traditional calibration and the simultaneous 3-axis calibration procedure is known, it is possible, at least in first analysis, to provide defined corrective terms for each single axis, as a function of frequency. In the graph of Fig. 7, in percentage, the corrective terms are depicted.

4. A CASE HISTORY

During the last two years, at INRiM, several MEMS accelerometers have been characterized by using the proposed procedure. Manufacturers and costumers were interested in the calibration of several series of 3-axial MEMS accelerometers at 160 Hz and 1 kHz, in particular used in wind turbine blade monitoring, at least within an accuracy of 10%. Tests have been carried out within the accuracy of 5%.

By using the test-rig depicted in Fig. 3, the simultaneous 3-axis calibration has been performed. A three-axial reference accelerometer (PCB type 356A15) has been fixed on the back of the table, as a supplementary controller. Data of sensitivity accuracy, with the respect of traditional calibration, have been corrected by using correction terms shown in the graph of Fig. 7. In the graphs of Fig. 8 and Fig. 9, as an example, the accuracy of measured sensitivity (in percentage) of 15 MEMS accelerometers, is depicted.

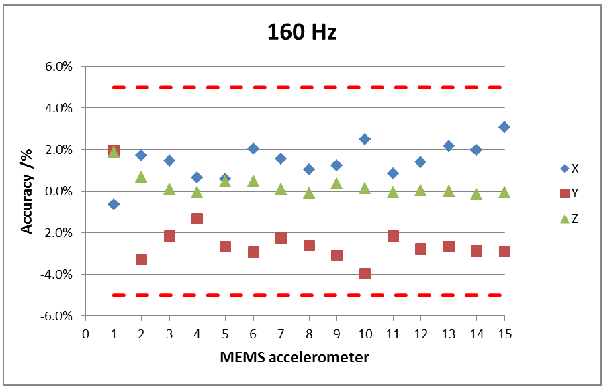

Fig. 8. Accuracy of 3-axis sensitivity at 160 Hz for a series of 15 different MEMS accelerometers.

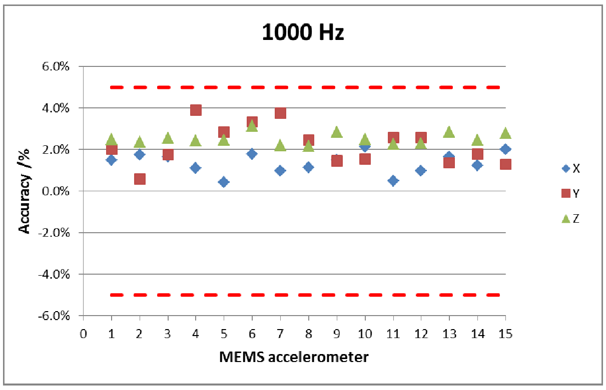

Fig. 9. Accuracy of 3-axis sensitivity at 1 kHz for a series of 15 different MEMS accelerometers.

REFERENCES

[1] X. Chen, K. Makki, K. Yen, N. Pissinou, "Sensor Network Security: A Survey", IEEE Communications Surveys & Tutorials, 11 (2); 2009.

[2] K. Sharma, S. Maheshwari, R. Solanki, V. Khanna, "Railway track breakage detection method using vibration estimating sensor network: A novel approach", Advances in Computing, Communications and Informatics; p. 2355-2362, 2014.

[3] Y. M. Hong, J. R. Zeng, Y. C. Kan, H. C. Lin, "The Development of Vibration Frequency Measurement Equipment for Bridge Pier", Advanced Science and Technology Letters, 63, p. 36-40, 2014.

[4] Y. Yu, J. Ou, "Wireless sensing experiments for structural vibration monitoring of offshore platform", Frontiers of Electrical and Electronic Engineering in China, 3(3), p. 333-337, 2008.

[5] O. Kreibich, J. Neuzil, R. Smid, "Quality-Based Multiple-Sensor Fusion in an Industrial Wireless Sensor Network for MCM", Industrial Electronics, IEEE Transactions, 61 (9), p. 4903-4911, 2014.

[6] C. J. Deng, H. Y. Hu, J. Z. Ling, "Software Test of Wireless Vibration Nodes of Nuclear Power Plants", Applied Mechanics and Materials, 336, p. 313-318, 2013.

[7] A.Umeda, M. Onoe, K. Sakata, T. Fukushia, K. Kanari, H. Iioka, T. Kobayashi, "Calibration of three-axis accelerometers using a three-dimensional vibration generator and three laser interferometers", Sensors and Actuators A: Physical, 114(1), p. 93-101, 2004.

[8] A. Nakano, Y. Hirai, K. Sugano, T. Tsuchiya, O. Tabata, A. Umeda, "Rotational motion effect on sensitivity matrix of mems three-axis accelerometer for realization of concurrent calibration using vibration table", MEMS 2013, Taipei, Taiwan, January 20 – 24, p. 645 – 648, 2013.

[9] ISO 16063-21:2003, Methods for the calibration of vibration and shock transducers -- Part 21: Vibration calibration by comparison to a reference transducer.

[10] A. Carpinteri, G. Lacidogna, G.Niccolini, "Acoustic emission monitoring of medieval towers considered as sensitive earthquake receptors", Natural Hazards and Earth System Science, 7(2), p. 251-261, 2007.

[11] G. Niccolini, A. Schiavi, P. Tarizzo, A. Carpinteri, G. Lacidogna, A. Manuello, "Scaling in temporal occurrence of quasi-rigid-body vibration pulses due to macrofractures", Physical Review E, 82(4), 2010.

[12] A. Carpinteri, S. Invernizzi, G. Lacidogna, A. Manuello, "Preservation, safeguard and valorization of masonry decorations in the architectural historical heritage of Piedmont (Italy)", Advanced Materials Research, 133, p. 1015-1020, 2010.

[13] G. Niccolini, A. Carpinteri, G. Lacidogna, A. Manuello, "Acoustic emission monitoring of the Syracuse Athena temple: scale invariance in the timing of ruptures", Physical review letters, 106(10), 2011.

[14] A. Schiavi, G. Niccolini, G. Lacidogna, A. Carpinteri, "Damage Assessment in Syracuse Limestone Specimens by Frequency Analysis of Elastic Emissions", Experimental and Applied Mechanics, Volume 4. Springer New York, p. 105-109, 2013;

[15] G. D'Emilia, A. Gaspari, E. Natale, "Calibration uncertainties of three-axis low frequency accelerometers: Test-rig and procedure aspects", IX MMT Conference proceeding, Ancona, p. 75-81, 2014.