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Abstract

Operational Modal Analysis is currently applied in structural dynamic monitoring studies using conventional wired based sensors and data acquisition platforms. This approach, however, becomes inadequate in cases where the tests are performed in ancient structures with esthetic concerns or in others, where the use of wires greatly impacts the monitoring system cost and creates difficulties in the maintenance and deployment of data acquisition platforms. In these cases, the use of sensor platforms based on wireless and MEMS would clearly benefit these applications. This work presents a first attempt to apply this wireless technology to the structural monitoring of historical masonry constructions in the context of operational modal analysis. Commercial WSN platforms were used to study one laboratory specimen and one of the structural elements of a XV century building in Portugal. Results showed that in comparison to the conventional wired sensors, wireless platforms have poor performance in respect to the acceleration time series recorded and the detection of modal shapes. However, for frequency detection issues, reliable results were obtained, especially when random excitation was used as noise source.

Operational Modal Monitoring of Ancient Structures using Wireless Technology

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NOMENCLATURE

f	Natural Frequency of the system
ξ	Damping coefficient
ω_k	Process noise
v_k	Measured noise
x_k	Discrete-time space state vector
y_k	Observation vector
A	Discrete-time state matrix
B	Discrete-time input matrix
C	Discrete-time output matrix
D	Discrete-time direct transmission matrix
h	Hankel matrix
j	Number of columns in the Hankel Matrix
Y_f	Future information of the Hankel matrix
Y_f^{ref}	Past information of the Hankel matrix
L,Q	Factors from a LQ factorization
Λ	Eigenvalues matrix
S	Observability matrix
Ψ	Complex modes shape matrix
Φ	Eigenvectors matrix
λ	Real eigenvalues or real eigen frequencies

ABSTRACT

Operational Modal Analysis is currently applied in structural dynamic monitoring studies using conventional wired based sensors and data acquisition platforms. This approach, however, becomes inadequate in cases where the tests are performed in ancient structures with esthetic concerns or in others, where the use of wires greatly impacts the monitoring system cost and creates difficulties in the maintenance and deployment of data acquisition platforms. In these cases, the use of sensor platforms based on wireless and MEMS would clearly benefit these applications. This work presents a first attempt to apply this wireless technology to the structural monitoring of historical masonry constructions in the context of operational modal analysis. Commercial WSN platforms were used to study one laboratory specimen and one of the structural elements of a XV century building in Portugal. Results showed that in comparison to the conventional wired sensors, wireless platforms have poor performance in respect to the acceleration time series recorded and the detection of modal shapes. However, for frequency detection issues, reliable results were obtained, especially when random excitation was used as noise source.

1. INTRODUCTION

For most advanced economies, buildings represent one of the largest single investments of national resources. While recently built buildings are very important, there are other existent structures that require even more attention. The permanent study of ancient buildings, which represents the architectural heritage of a region, is a key aspect to modern societies since the impact of a possible loss is not only economical but also cultural. This work intends to contribute on the process of preservation of the architectural heritage.

In this line, it is intended to evaluate possible damages and to perform structural monitoring according to the modern strategies of minimum repair and the use of non intrusive methods. On the latter, the advancements on Micro-Electro-Mechanical Systems (MEMS) and the wide range of alternatives on wireless communications are turning Wireless Sensor Network (WSN) technology into a promising candidate to develop new structural monitoring solutions for this research area. With this respect, the aim of this work was to rely on commercially available wireless and MEMS technology in real operational modal analysis case studies to evaluate their capabilities and state future research lines.

The paper starts by describing the conventional wired based and wireless based sensors and data acquisition equipments (DAQ) used for structural dynamic monitoring works. Operational modal analysis is then overviewed by describing the SSI method as it was used as data processing tool in the experimental tests. Furthermore, two case studies where the WSN platforms were used to perform operational modal analysis are shown and discussed. Finally, a new WSN platform, which is being built as part of future developments, is presented as well as the conclusions.

2. DYNAMIC MONITORING SYSTEMS FOR CIVIL ENGINEERING STRUCTURES

During the past years significant hardware developments occurred for structural monitoring purposes. Conventional monitoring sensors used for these applications, involve a large number of wires (fiber-optic cables or other wired communication medium) and centralized data acquisition systems with remote connections. The fact that the conventional sensor platforms use wires increases the cost of the monitoring systems, creates difficulties in the maintenance and deployment in the field. In this line, the recent years have witnessed an increasing interest in a new technology based on WSN platforms as a low-cost alternative for being applied in civil engineering structures [1].

2.1 Wired Based Monitoring Systems

The wired based systems (also called in this work as conventional systems) used for structural monitoring are composed by three parts: measurement sensors, data acquisition equipments and, in some cases, remote connection systems. The measurement sensors are connected with cables to the data acquisition systems which can also be remotely connected to a central station.

The conventional measurement sensors used for dynamic identification tests are piezoelectric, piezoresistive, capacitive or force-balanced accelerometers. For data acquisition purposes, platforms with capabilities of medium sampling rates (around 2000 Hz) and Analog Digital Converters (ADCs) with resolutions over than 16 bits are chosen. In the case of the remote connection systems the most popular approaches include the use of IEEE

802.11a, b, and g standards or cellular data (such as CDMA, GSM/GPRS, EDGE, and so on) for communication purposes [2]. Figure 1 shows an example of piezoelectric sensors and USB data acquisition systems.

(a) (b) (c)

Figure 1 - Conventional equipments used for dynamic identification. (a) Accelerometers models PCB 393B12 and WR 799M [3], [4]; (b) and (c) USB data acquisition equipment models NI USB-9233 with 24 bits and NI SCXI-1531 with 16 bits [5].

2.2 Wireless Based Monitoring Systems

The use of wireless technology with embedded MEMS for structural monitoring was first proposed by [6], [7], [8] and, [9]. In those works, the authors proposed the integration of wireless communications with sensors to develop a near real-time monitoring system of structures. Since then, a lot of academic efforts to improve the technology have been made.

The first WSN platform was developed by the University of California-Berkeley and subsequently commercialized by Crossbow [10] since 1999. Since then, this commercial technology has been constantly advancing. In Ref. [11] a compilation that highlights the state of the art of this type of sensors up to 2005 is presented and is resumed in Figure 2.

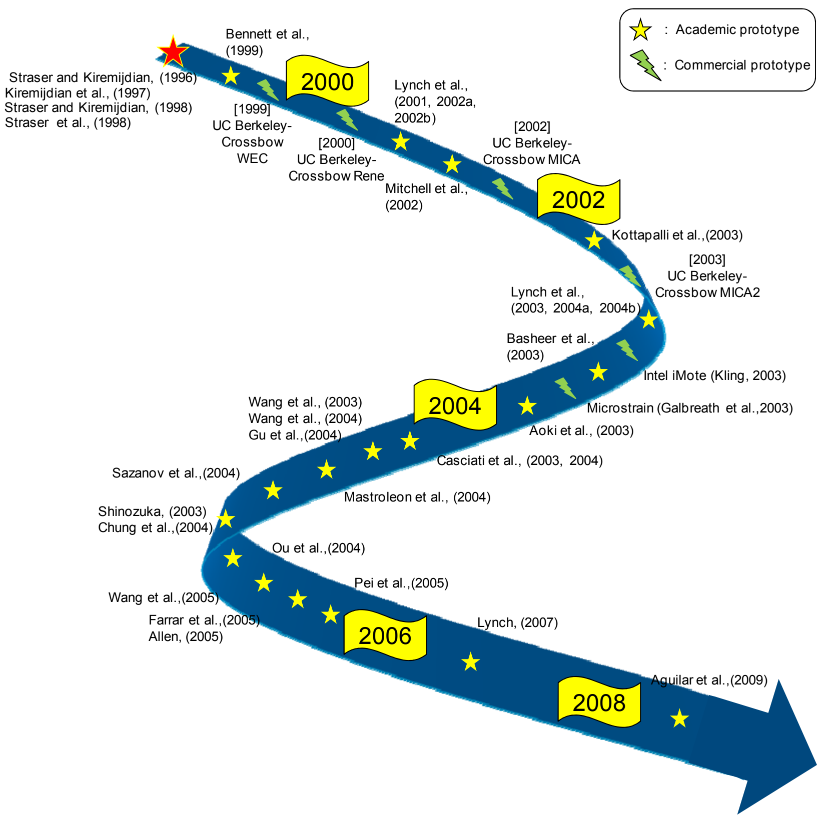


Figure 2 - Overview of the state of the art of wireless technology for structural monitoring

A monitoring system based on WSN platforms with embedded MEMS is composed by three parts: 1) Measurement units, 2) base station and, in some cases, 3) remote connection system. The equipments and the technology used for the third part of the system (remote connection) are, most of the times, the same as the ones used in the conventional systems.

The measurement units are composed of several sensing interfaces with embedded MEMS. MEMS are an emerging technology through which miniature mechanical systems are built using the standard Integrated Circuits technologies on the same chip as the electronic circuitry. The main advantage of MEMS is that, because of the high effectiveness used in their fabrication process, these can perform measurements with relatively low cost and low power consumption [12]. There are several commercially available MEMS-based transducers like micro-accelerometers, temperature, humidity and, pressure micro-sensors.

Besides the obvious issues related to energy consumption, there are other aspects related to the measurement sensors and DAQ characteristics to consider when these platforms are being evaluated as an alternative of conventional systems. Commercial micro-accelerometers are primarily made based on the capacitive principle, are able to measure in 1, 2 or 3 axis configuration with a range of measurement from ±2 g to ±400 g and low resolutions (in comparison to conventional platforms). For operational modal analysis, platforms which have embedded microaccelerometers able to measure at least in a range of ±2 g with the higher resolution available should be chosen. Another important aspect to take into account are the DAQ systems embedded in the platforms. As it was previously shown, conventional systems have high resolutions over 16 bits; unfortunately, commercial platforms are only equipped with ADCs with low resolutions varying from 10 bits to 12 bits.

3. OPERATIONAL MODAL ANALYSIS OF CIVIL ENGINEERING STRUCTURES

For dynamic monitoring, the first and natural tendency of civil engineering researchers was to take profit from important previous developments made in the area of system identification and experimental modal analysis in the electrical and mechanical engineering. Depending on the excitation source, two different groups of techniques are currently used for performing structural dynamic monitoring, the Input-Output and the Output-Only techniques.

Nowadays Output-Only techniques (also called operational modal analysis) in which the structures are excited just by ambient noise are desirable and commonly used due to the higher costs and difficulties involved in the Input-Output Tests [13]. Output-Only methods are based on the premise that wind, traffic and human activities can adequately excite structures.

The main assumption of the Output-Only identification methods is that the ambient excitation input is as a Gaussian white noise stochastic process in a frequency range of interest. Due to the random nature of the excitation, the response includes not just the modal contributions of the ambient forces and the structural system but also the contribution of the noise signals from undesired sources. For this reason, the identification techniques must have the ability to separate the noise modes.

Considering previous experiences, when dynamic monitoring works are performed, there is no perfect method that can be generally applied. However, the Stochastic Subspace Identification method (SSI) or its variants is the method that gives more reliable results in most of the cases and so, the one that is used in this work.

The stochastic subspace identification (SSI) method was originally proposed by [14] and then modified (SSI-Data method) by [15]. The Data-Driven Stochastic Subspace Identification method (SSI-Data) is based on the stochastic space model theory from output-only measurement and has as focus the identification of the state matrix A and the output matrix C, which contains the modal information of the studied system. The SSI method uses robust numerical techniques such as QR-factorization, singular value decomposition (SVD) and least squares. The QR-factorization results in a significant data reduction, whereas the SVD is used to reject system noise. The method is summarized in Figure 3.

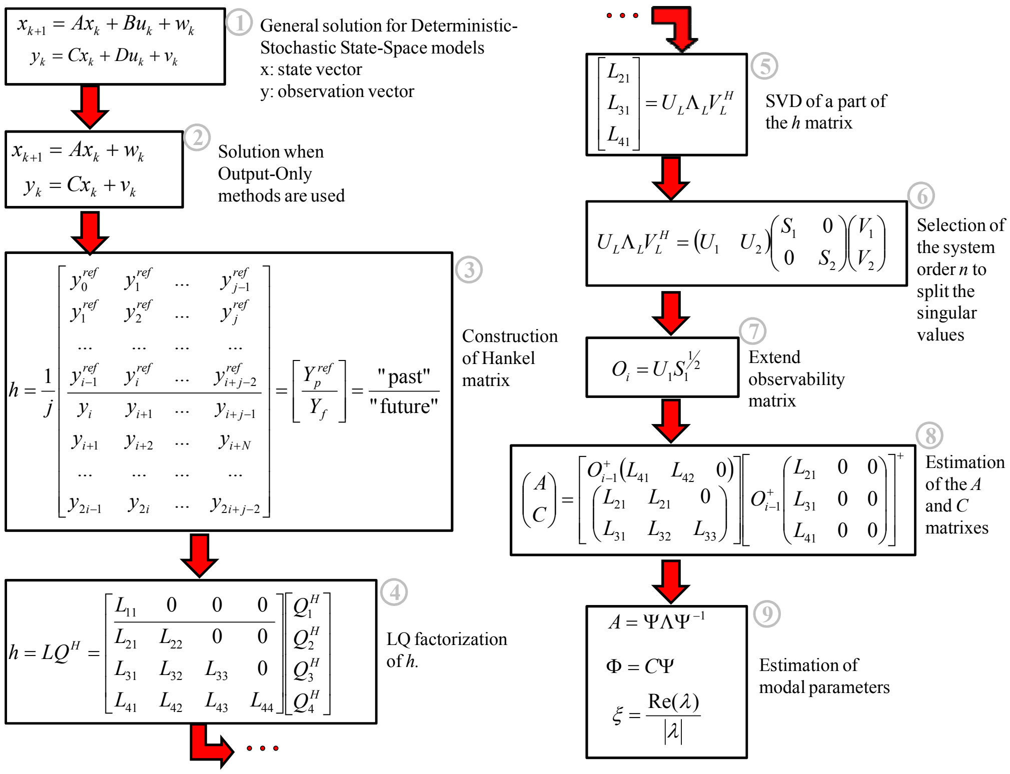


Figure 3 - Flow chart of the SSI-DATA method.

4. OPERATIONAL MODAL ANALYSIS OF ANCIENT STRUCTURES USING WIRELESS PLATFORMS

4.1 Sensors and Data Acquisition Equipments

In this work, conventional wired monitoring systems with accelerometers, data acquisition equipments and commercial WSN platforms were used for performing the experimental studies.

The conventional wired monitoring systems used the high sensitivity piezoelectric accelerometers model PCB 393B12 [3]. For the conventional data acquisition equipment the NI-USB9233 platform [5] which offers ADC resolution of 24 bits was selected.

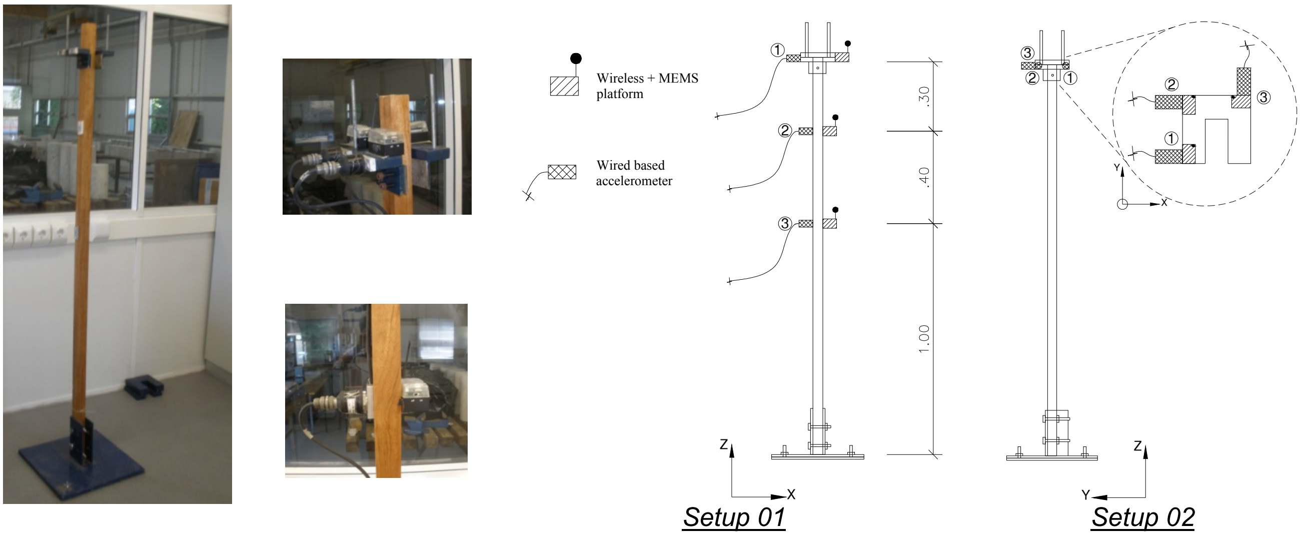
For the WSN platforms, Crossbow technology [10] was chosen as they offer a low-cost solution and low power boards with embedded micro-accelerometers.

Two case studies were carried out with the aim of comparing the performance of the WSN platforms with respect to the conventional wired based systems and assess the possibility of their use to perform operational modal analysis of civil structures. Details, results and comments of the tests are following shown.

4.2 Case study I: Dynamic response of an inverted Pendulum

A single degree of freedom structure represented by an inverted pendulum is one of the simplest examples that are used by civil engineers to explain the fundamentals of the dynamics of structures. In this work, this structure is also used as a tool to evaluate and understand the behavior of the commercial wireless based platforms and their utility for engineering works.

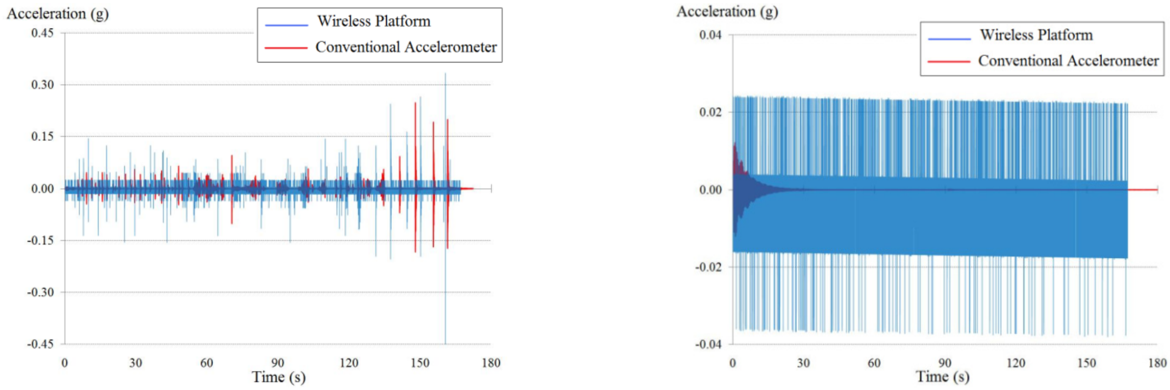
The specimen consists in an inverted pendulum with 1.70 m high built by wood with steel plates in its top and base (Figure 4a). To perform a complete dynamic characterization of the pendulum, three conventional wired based one-axis accelerometers and three wireless + MEMS platforms working with their accelerometers only in one direction were used. These sensors were arranged in two setups where the node 1 was kept as common for both measurements as shown in Figure 4b, Figure 4c and Figure 4d. For comparison purposes the wired and wireless systems were set for running in parallel. The data acquisition was done at a sampling rate of 128 Hz.



(a) (b) (c) (d)

Figure 4 - Description of the case study I. (a) Inverted Pendulum in the laboratory; (b) Close up of the wired and wireless based sensors arrangement; (c) Setup 01 description and; (d) Setup 02 description.

The first analysis consists on the study of the performance of the wireless platforms with respect to the conventional sensors by means of the acceleration time series collected. With this purpose, tests under random excitation and under ambient noise were performed. The Figure 5 shows the recorded signal by mote 3 and by accelerometer 3 in both scenarios.



(a) (b)

Figure 5 - Time series collected by mote and accelerometer # 03 in the tests of the Pendulum. (a) Response under random excitation in Setup 01 and; (b) Response under ambient noise in Setup 02

The results evidence the poor performance of the MEMS micro-accelerometers embedded in the wireless platforms for measuring vibrations with low amplitude. In the case when random noise was exciting the structure the maximum peaks detected by the wireless platforms vary in an range of 2 to 9 times while when ambient noise is used as source of excitation, the maximum peaks detected vary from 3 to 6 times with respect to the peaks detected by the conventional wired based accelerometers.

Using again ambient and random noise as source of excitation, the second analysis performed in the specimen consists on the study of its dynamic properties.

For determining the dynamic properties of the system the SSI method, which is implemented in the ARTeMIS extractor software [16], was used. In Figure 6 the stabilization diagram corresponding to the random excitation system is shown. The Table 1 shows a resume of the results of the wireless and conventional accelerometers.

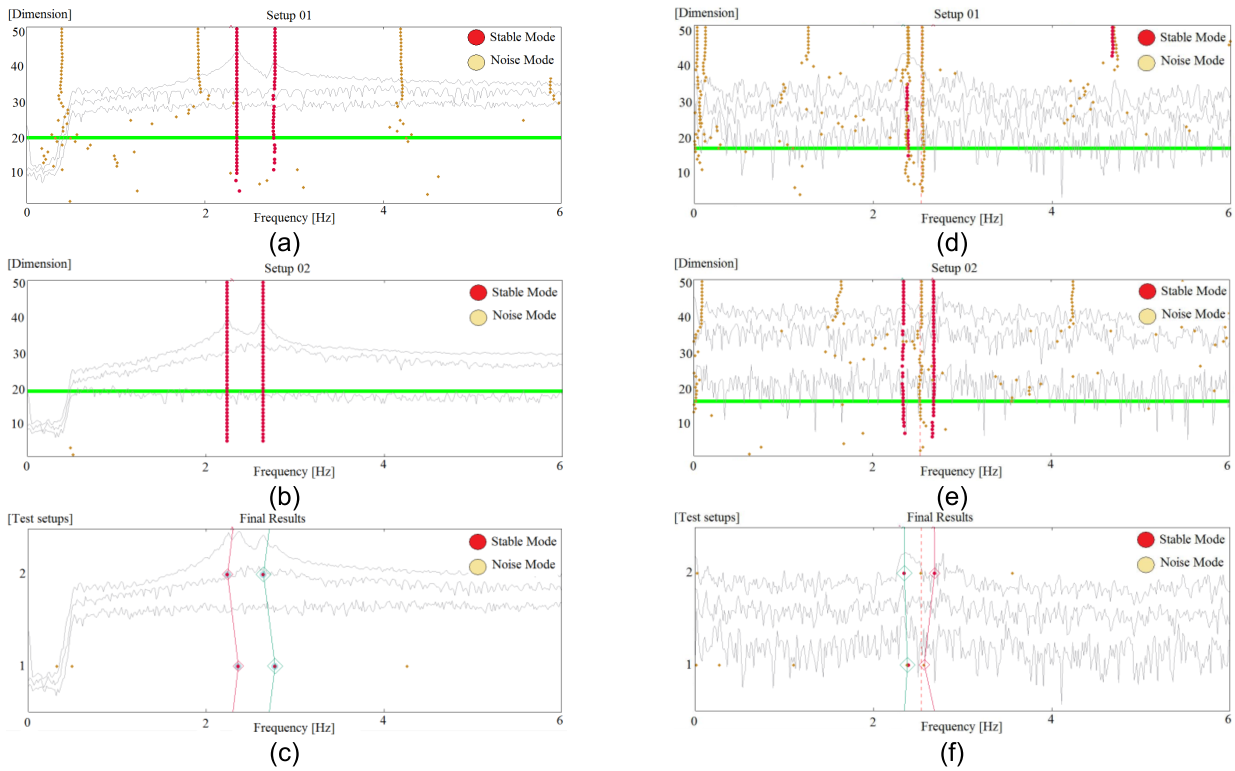


Figure 6 - Stabilization diagrams of the analysis of the time series recorded under random excitation in the Pendulum tests. (a) (b) and (c) Results of the conventional wired based accelerometers; (d) (e) and (f) Results of the wireless platforms.

Table 1: Results of the dynamic response of the Pendulum

		Conv. Accelerometers		Wireless Platforms			
	Mode	f (Hz)	ξ (%)	f (Hz)	ξ (%)	f_{ERROR} (%)	ξ_{ERROR} (%)
Excited	1	2.30	1.45	2.35	3.57	2.13	59.39
	2	2.71	1.57	2.68	2.94	1.12	46.60
Ambient	1	2.26	0.82	2.41	9.82	6.22	--
	2	2.63	2.12	2.83	10.42	7.07	--

According to the frequency content, the results show that the wireless platforms give accurate results, even under environmental noise. When the structure is lightly and randomly excited the modal identification is easy because the stable poles are properly aligned in the natural frequencies. In the case of ambient noise the dynamic identification becomes more complicated for the appearance of noise modes in the stabilization diagrams (stabilization diagrams are not shown in this work); however interesting results were also achieved. Due to the lack of synchronization algorithms implemented on the motes, information about the mode shapes is useless.

4.3 Case study II: Dynamic Response of Monuments - The Chimneys at Paço dos Duques Building

The Paço dos Duques Building was built between 1422 and 1433 by D. Afonso (bastard son of the king of Portugal D. Joao I) in Guimarães located at the north of Portugal. In the beginning the building was used as a residence of the “Duques de Bragança” and was inhabited from 1480 to 1807 [17]. In 1807 the building was used as barracks and in 1888 the Architects and Archeologist Portuguese Society considered it as a historical monument [18]. In 1937 the building was re-built with the base of the available information and also new structural elements were introduced which gave the recent impressive character to the building. The Figure 7 shows the view of the actual situation of the building and its original condition before the intervention in 1937.

(a) (b)

Figure 7 - Paço dos Duques Building. (a) Actual situation [19] and; (b) Front view of the palace in 1935 [18].

One of the most important changes in the structure was the addition of chimneys. The original building had only 4 chimneys and later in the intervention of 1937, 34 more chimneys were added. Since 2002 the building is under study and under restoration as well as preservation works. As part of those works, the structural analysis of the chimneys was considered due to the fact that those elements are the most damaged in the building.

Based on the previous reliable results of the experiments in the pendulum (case study I), the use of the commercial wireless platforms for structural dynamic monitoring was explored.

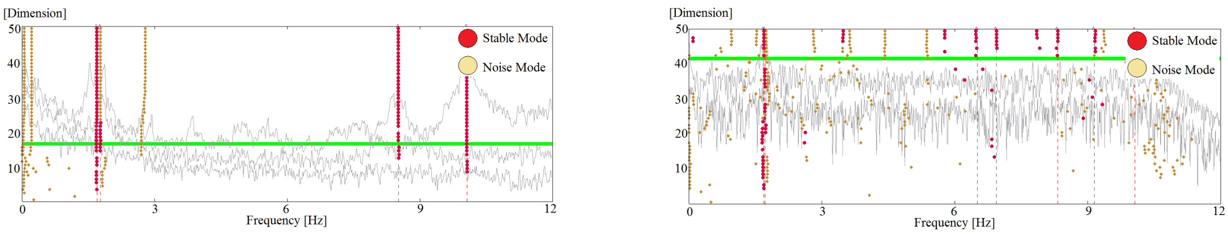
The dynamic response of one of the 4 original chimneys was studied using conventional and wireless platforms. The Figure 8 shows a general view of the restoration works that are being carried out and the wireless platforms placed in the studied chimney.

(a) (b)

Figure 8 - Chimneys at Paço dos Duques Building. (a) Current restoration works and, (b) Sensors location.

The advantages of using wireless platforms were evidenced in this case study. In addition to the economical aspects, the fact that the wireless platforms are lighter in comparison to the conventional accelerometers allowed to place them in an easier way on the surface of the chimneys. The data acquisition process was also easier allowing a safer work in difficult zones such as the roof of the building.

The Figure 9 shows the stabilization diagrams of the analysis of the time series recorded under random excitation. Table 2 shows the results of the identified frequencies using the conventional accelerometers and wireless platforms.



(a) (b)

Figure 9 - Stabilization diagrams of the analysis of the time series recorded under random excitation in the studied chimney at Paço dos Duques Building. (a) Results of the conventional wired based accelerometers and; (b) Results of the wireless platforms.

Table 2: Dynamic response of the studied Chimney at Paço dos Duques building

Mode	Conv. Accelerometers f (Hz)	ξ (%)	Wireless Platforms f (Hz)	ξ (%)	f_{ERROR} (%)	ξ_{ERROR} (%)
1	1.69	1.34	1.68	1.61	0.60	16.77
2	1.77	4.22	1.71	0.72	3.51	--

The results show small differences in the identified frequencies obtained by using the conventional and the wireless platforms. When the tests are performed with ambient noise (results are not shown in this work) the same frequencies could be identified but, as in the previous experience on the pendulum, with more difficulties as more noise modes appear in the stabilization diagrams.

5. NEW WIRELESS PLATFORM TO PERFORM STRUCTURAL DYNAMIC MONITORING WORKS

Since the strengths and weakness of the commercial wireless platforms were identified, current works are now oriented to develop a new platform to fulfill the requirements of the operation modal analysis of civil structures.

The limitations of the commercial WSN platform for performing operational modal analysis can be synthesized in the following aspects: not enough resolution of the microsensors and DAQ systems embedded in the platforms, lack of synchronization algorithms, data loss issues and, no solutions available related to energy consumption. As a first stage of the developing works it was intended to board the first 3 aspects as, in this stage, long term monitoring is out of the scope. The last aspect will be considered in future stages of the research works.

In this first stage, it was considered to specify, develop and produce a new sensing device capable of measuring low amplitude accelerations. It is also considered that the new device will be compatible with current commercial-of-the-shelf WSN platforms capable of supporting standard communication protocols IEEE 802.15.4 protocol, as well as the OpenZB communication stack [20].

At the moment, the new wireless platform is under construction. With this new tool it is scheduled to perform future validation tests in laboratory specimens and also in real monuments.

6. CONCLUSIONS

This paper explores a new tool based on wireless technology with embedded MEMS sensors for performing operational modal analysis of structures. With this respect, commercial WSN platforms available in the market were chosen for being studied by comparing their performance against well known and tested conventional wired based systems.

The results of the laboratory tests showed that these platforms have poor performance with respect to the acceleration time series recorded due to the low resolution of the microaccelerometers and DAQ systems embedded. The wireless platforms showed also poor performance for the detection of modal shapes. In the case of frequency detection, reliable results were obtained especially when the systems were randomly excited.

In order to study the performance of the wireless platforms in the field, a second series of tests was carried out in the chimneys of a historical XV century monument in Portugal. Interesting results were achieved once again in the frequency detection task of the modal analysis process. In this case, very small differences were detected between the measured frequencies with conventional and wireless platforms.

With the obtained results, the problems of the commercial wireless platforms and their application for civil engineering studies were identified. Future works are based on the development of a new wireless sensing board considering this time microaccelerometers and DAQ systems with higher resolutions and the implementation of standard communication protocols.

7. ACKNOWLEDGMENTS

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8. REFERENCES

[1] Ruiz-Sandoval, M.E. “Smart” sensors for civil infrastructure systems. PhD Thesis, University of Notre Dame (2004).

[2] NI. Overview of Structural Health Monitoring Solutions. www.ni.com (2009).

[3] PCB. Product Catalog, (2007).

[4] http://www.wilcoxon.com/. Wilcoxon Research, Inc. (2009).

[5] NI. User guide and specifications. www.ni.com (2009).

[6] Straser, E.G. and Kiremijdian, A.S. A modular visual approach to damage monitoring for civil structures. Proceedings of SPIE v2719, Smart Structures and Materials (1996).

[7] Kiremijdian, A.S.; Straser, E.G.; Meng, T.H.; Law, K. and Soon, H. Structural damage monitoring for civil structures. International Workshop - Structural Health Monitoring (1997).

[8] Straser, E.G. and Kiremijdian, A.S. A modular, wireless damage monitoring system for structures. The John A. Blume Earthquake Engineering Center (1998).

[9] Straser, E.G.; Kiremijdian, A.S.; Meng, T.H. and Redlefsen, L. A modular wireless network platform for monitoring structures. Proceedings – SPIE The International Society for Optical Engineering (1998).

[10] Crossbow. MoteWorks Getting Started Guide, Crossbow (2008).

[11] Lynch, J.P. and Loh, K.J. A Summary Review of Wireless Sensors and Sensor Networks for Structural Health Monitoring. The shock and vibration digest (2006).

[12] Stiharu, I. MEMS, general properties, Encyclopedia of vibration. Academic Press (2002).

[13] Doebling, S.W.; Farrar, C.R. and Cornwell, P. A Statistical Comparison of Impact and Ambient Testing Results from the Alamosa Canyon Bridge, International Modal Analysis Conference (1997).

[14] Van Overschee, P. and De Moor, B. Subspace algorithms for the stochastic identification problem. Proceedings of the 30th Conference on Decision and Control, Brighton, England, (1991).

[15] Peeters, B. and De Roeck, G. Reference-based stochastic subspace identification for output-only modal analysis. Mechanical Systems and Signal Processing. Academic Press, 855-878 pp, (1999).

[16] SVS. ARTEMIS extractor pro user manual, Release 4.5. Structural Vibration Solutions (2009).

[17] Azevedo. A. Paço dos Duques, Livraria Lemos (1964).

[18] Silva, J. H.P. Paço dos Duques em Guimaraes, Secretaria de Estado de Informacao e Turismo (1974).

[19] http://www.bing.com/maps/ (2009).

[20] http://www.open-zb.net. Open-ZB open-source toolset for the IEEE 802.15.4/ZigBee protocols website (2009).