Implementation of a Wireless Sensor Network In a Three Story Building

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SUMMARY

In general, one of the first steps to achieve damage detection is to establish the dynamic characteristics of the structure. In practice, this is usually done placing sensors in specific locations according to number of modes required to be detected. Recently, new methodologies and equipment are available for structure's instrumentation. Wireless technology allows placing several sensors over the structure without the need of a high budget. Wireless sensors applications are new and in some countries non-existent.

This paper presents the results obtained from a wireless sensor network in the capture of the dynamic characteristics of a three story building. The objective is to compare identified systems throughout the records obtained from wireless and wire sensors with respect of a mathematical model.

Keywords: wireless sensors, sensor placement, system identification

1. INTRODUCTION

The instrumentation of structures has been recently becoming popular. One of the principal limitations to its implementation is the cost of the system, as well as their maintenance over time. Nowadays, new technology allows reducing the investment in the equipment. Sensors with wireless capabilities have lower prices, reaching a fifth of the value compare with traditional wire systems. The main advantage is the absence of cables. However this also brings new challenges to be overcome.

The number, type and location of the sensors required for the instrumentation will depend on the desired objective. In particular, for a dense array of sensors generally allows capturing a considerable number of natural periods, as well as mode shapes. Nevertheless, special emphasis should be put in the location and direction of sensing over the structure.

Other important aspect to be considered is the selection of the discrete parameters in the data acquisition system. These parameters include sample rate, length and set of the records to be capture. An incorrect selection of these parameters could hinder an adequate dynamic characterization of the structure.

Finally, wireless sensors have some limitations, especially in memory and radio range. Also, because each sensor has an independent clock, time synchronization is required prior data collection. There exist different types of devices; however open sources platforms have the advantage to be customized according to the needs of the user.

The research reported herein provides a methodology for wireless instrumentation of structures. Presents a sequence of steps to determine the optimal place of the sensors, these are based according with the number of modes desired to be capture. An open source wireless system is used that includes a synchronization scheme. A comparison between wire, wireless and analytical results is presented.

2. STUDIED STRUCTURE

The selected building is located in north part of Mexico City. The structure belongs to the Autonomous Metropolitan University, campus Azcapotzalco (UAM-A). The building has the name 4p. The function of the building is to allocate the Materials Department and professor's offices.

The structure has three levels, each one with a height of 3m therefore with a total height of 9 m. The structure has a rectangular shape with 28.25 m of front and 9.4 m of depth. It has 2 and 5 bays in the transversal and longitudinal direction respectively. The dimensions of the columns and beams are 0.45 x 0.60 m and 0.25 x 0.45 m. The columns are placed so the strong axis in the transversal direction. Figure 1 shows a plan floor of the structure.

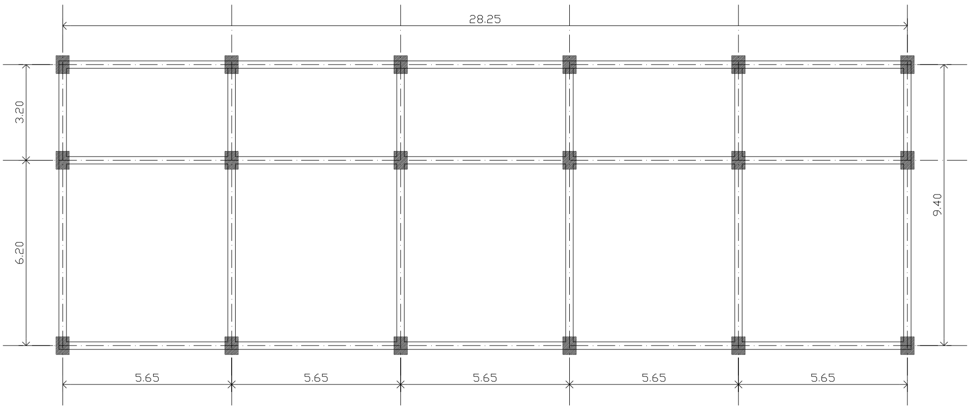


Figure 1. Plant distribution of elements of structure 4p

3. SENSORS UTILIZED

3.1. Wire sensors

The wire sensors used to instrument the building were the 2 PCB 3701G3FA3G (PCB 2012) and 2 PCB 393B04 (PCB 2012). The first two sensors are capacitive, while the last two are piezoelectric. The data acquisition system employed was the DSPT SigLab 20-42 box. This system has a 20-bit sigma-delta analog to digital (A/D) converter with a 90 dB antialiasing filter.

3.2. Wireless sensors

The Imote2 wireless sensors were used to instrument the building (Memsic 2012). The Imote2 consist of three parts; a case for batteries, the main board (allocating the microprocessor, radio and memory), and the sensor board. The microprocessor is an Intel PXA271 XScale with a clock speed of 416 MHz. The analog digital converter has 16 bits. The radio communication uses the ZigBee 802.15.4 protocol. It has 32 MB of flash memory.

The sensor board contains the tri-axial accelerometer LIS344LH with a maximum acceleration capacity of +/- 2g. The sensitivity is 500mV/g. It also has the QF4A512 programmable filter. With the integrated antenna the range of communication goes up to 30 meter; however an external antenna can be attached giving the system up to 100 meters of wireless communication.

4. OPTIMAL SENSOR PLACEMENT

There are different proposals for optimal sensor placement. These differ according with objective of the instrumentation as well as for the type of sensors to be employed. In general, independently of these constraints, having a dense array of sensors would allow to better characterize the structure. However, in many cases only a limited number of devices are available, so a study to determine its best locations is required.

The sensor placement for simple structures can be determined based in the experience of the engineer, or inclusive throughout a trail an error approach. However, for complex structures this task is not easy and it is necessary to overcome the subjectivity of the engineering judgment by doing an analysis of the dynamic parameters of the structure.

In the case of sensor and actuator placing, Gawronski and Lim (1996) presented a methodology based in the Hankel matrix. They demonstrate that the singular value decomposition of the matrix helps determine the best observability and controllability of the system. It is shown that if the trace of the singular value matrix is used for the placement of the sensors, then the placement of the actuator becomes trivial.

Cherng (2003) proposed a methodology based in the methods of Lim-Gawronski (LG) and Bayard-Hadaegh-Meldrum (BHM). This method was used to achieve the optimal sensor placement in this study. A summary of the methodology is presented.

4.1. Method LG

This method uses a matrix Γ_{LG} that is defined as the trace of the product H^TH of the Hankel matrix. (H).

$$\gamma^2 = trace(H^T H) = \sum_{i=1}^{m} \left\{ \sum_{r=1}^{n} \tilde{\gamma}_{ir}^2 \right\} \tag{4.1}$$

Where *m* is the number of sensor locations and *n* is the target modes.

Γ_{LG} matrix has a dimension of *m* x *n*. Each column represents the distribution of energy (γ) of each mode in each sensor location (*m*). Each row represents the contribution of each sensor (*n*) in each mode (*n*)

$$\Gamma_{LG} = \begin{bmatrix} \tilde{\gamma}_{11}^2 & \tilde{\gamma}_{12}^2 & \cdots & \tilde{\gamma}_{1n}^2 \\ \tilde{\gamma}_{21}^2 & \tilde{\gamma}_{22}^2 & \cdots & \tilde{\gamma}_{2n}^2 \\ \cdots & \cdots & \cdots & \cdots \\ \tilde{\gamma}_{m1}^2 & \tilde{\gamma}_{m2}^2 & \cdots & \tilde{\gamma}_{mn}^2 \end{bmatrix} \tag{4.2}$$

The location index φ_i is then defined according with the following expression.

$$\varphi_i = \frac{\gamma_i^2}{\gamma^2}, \qquad 0 \le \varphi_i \le 1$$
$$\sum_{i=1}^{m} \varphi_i = 1 \tag{4.3}$$

If the index φ_i has the value of 1 that means that the sensor location would capture all the targeted modes of the structure. The method is based in the capture contribution of the energy by the sensor for the mode *n* at the location *m*. This is similar to an arithmetic mean method.

4.2. Method BHM

Cherng (2003) mentioned the BHM method uses the sum up of each modal contribution over all the sensor locations, and later ranks the product of these contributions. The method BHM uses the contribution matrix Γ_{BHM} in terms of the mode shapes ϕ, and is define as:

$$\Gamma_{BHM} = \begin{bmatrix} \phi_{11}^2 & \phi_{12}^2 & \cdots & \phi_{1n}^2 \\ \phi_{21}^2 & \phi_{22}^2 & \cdots & \phi_{1n}^2 \\ \vdots & \vdots & \ddots & \vdots \\ \phi_{m1}^2 & \phi_{m1}^2 & \cdots & \phi_{mn}^2 \end{bmatrix} \tag{4.4}$$

For this method the placement index is the following:

$$\psi = \prod_{r=1}^{n} \|\phi_r\| \tag{4.5}$$

This method allows the evaluation of the modal contribution that can be performed mode by mode. For different targeted modes (modes that are desired) there could be different combinations, therefore the beast position is obtained trying different combinations of sensor locations.

4.3. Method Cherng

Based on the previous approaches, Cherng proposed a combination of LG and BHM methods. It starts by the normalization of the contribution of each sensor per mode. Doing this procedure it is assure that each mode has the same contribution in the matrix Γ.

$$\Gamma = \begin{bmatrix} \tilde{\rho}_{11}^2 & \tilde{\rho}_{12}^2 & \cdots & \tilde{\rho}_{1n}^2 \\ \tilde{\rho}_{21}^2 & \tilde{\rho}_{22}^2 & \cdots & \tilde{\rho}_{2n}^2 \\ \vdots & \vdots & \ddots & \vdots \\ \tilde{\rho}_{m1}^2 & \tilde{\rho}_{m2}^2 & \cdots & \tilde{\rho}_{mn}^2 \end{bmatrix} \tag{4.6}$$

Where

$$\rho_{ir} = \frac{\tilde{\phi}_{ir}^2}{\sum_{r=1}^{m} \tilde{\phi}_{ir}^2} \tag{4.7}$$

So, the contribution of each sensor over all the targeted modes is:

$$\rho = \sum_{r=1}^{n} \rho_{ir}, \qquad 0 \le \rho_i \le n \tag{4.8}$$

And

$$\sum_{i=1}^{m} \rho_i = n \tag{4.9}$$

Finally, the placement index can be obtained using the following equation

$$\psi = \prod_{r=1}^{n} \sum_{i=1}^{m} \rho_{ir} = \prod_{r=1}^{n} \|\mathrm{p}_r\|_1 \tag{4.10}$$

The best combination for the sensors would give a higher value at this index.

The methodology proposed by Cherng will be used in this work. As described previously, this method normalized the contribution of each sensor, therefore each mode has the same importance and the sensor placement is not rule by a particular mode. Furthermore, the placement index is based in the combination of the available sensor contributions, so it is easier to program and to deal with when the model provides with plenty of information.

5. APPLICATION EXAMPLE FOR A SIMPLE 3D MODEL

A simple model of four columns and fours beams was constructed. This model is presented in figure 2.

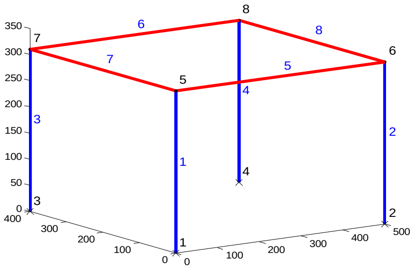
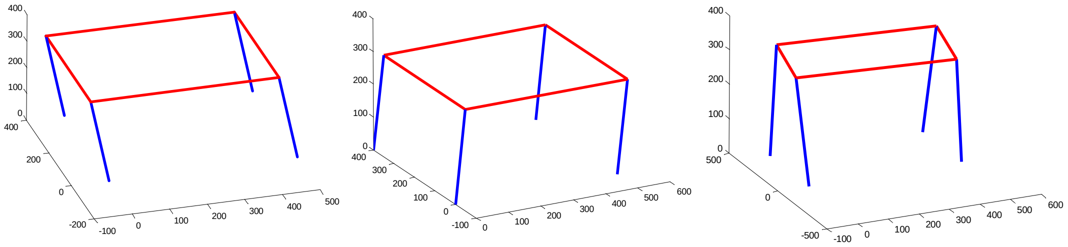


Figure 2. Simple 3d model with 8 nodes and 8 elements.

The first natural frequencies and mode shapes were determined. Only the first 3 frequencies were used as the targeted modes. Figure 3 shows the mode shapes.



a) First mode b) Second mode c) Third mode

Figure 3. Mode shapes of the model

The mode shapes were normalized and then the matrix Γ is constructed and presented in table 1.

Table 1. Matrix Γ of the simplified model

Node	Sensor	Normalized mode shapes		
		ρ_{i1}	ρ_{i2}	ρ_{i3}
5x	1	2.50E-01	6.00E-22	1.03E-01
5y	2	3.99E-22	2.50E-01	1.47E-01
5z	3	6.65E-07	1.07E-05	3.59E-06
5θx	4	3.46E-27	2.13E-06	1.13E-06
5θy	5	5.06E-06	1.21E-26	1.87E-06
5θz	6	1.12E-28	5.02E-31	1.25E-06
6x	7	2.50E-01	6.00E-22	1.03E-01
6y	8	8.83E-22	2.50E-01	1.47E-01
6z	9	6.65E-07	1.07E-05	3.59E-06
6θx	10	7.35E-27	2.13E-06	1.13E-06
6θy	11	5.06E-06	1.22E-26	1.87E-06
6θz	12	1.10E-28	5.85E-31	1.25E-06
7x	13	2.50E-01	6.30E-22	1.03E-01
7y	14	3.98E-22	2.50E-01	1.47E-01
7z	15	6.65E-07	1.07E-05	3.59E-06
7θx	16	3.46E-27	2.13E-06	1.13E-06
7θy	17	5.06E-06	1.27E-26	1.87E-06
7θz	18	1.12E-28	4.00E-31	1.25E-06
8x	19	2.50E-01	6.30E-22	1.03E-01
8y	20	8.71E-22	2.50E-01	1.47E-01
8z	21	6.65E-07	1.07E-05	3.59E-06
8θx	22	7.35E-27	2.13E-06	1.13E-06
8θy	23	5.06E-06	1.27E-26	1.87E-06
8θz	24	1.10E-28	4.97E-31	1.25E-06
Σ =		1	1	1

A conclusion from table 1 is that the contribution to any rotation degree of freedom is small or near to zero (E-06 to E-28). Given this behaviour no rotation sensors will be considered in any of the combinations.

In order to illustrate the best placement procedure, the instrumentation is limited with only two sensors. Table 2 presents the summary of the best placement combination.

Table 2. Sensor combinations for simplified model

Combinations	ψ
2,8	0.7938
2,14	0.7938
2,20	0.7938
8,14	0.7938
8,20	0.7938
14,20	0.7938

Any combination of two sensors provide with a maximum placement index of 0.79. This value could be increased only by the presence of more sensors in the structure.

For this particular structure exist completely symmetry. Given this property, the information collected in one of the corners will be the same than the others. Therefore the Γ matrix is reconstructed with only sensor 5 and ignoring the rotation degrees of freedom (see table 3)

Table 3. Modified Γ matrix

Node	Sensor	Normalized mode shapes		
		ρ_{i1}	ρ_{i2}	ρ_{i3}
5x	1	1.00E+00	2.40E-21	4.12E-01
5y	2	1.60E-21	1.00E+00	5.88E-01
5z	3	2.66E-06	4.29E-05	1.44E-05

Finally, the new placement index ψ is presented in table 4.

Table 4. Sensor combinations for simplified model

Comb	ψ
1,2	2.9999
1,3	1.4124
2,3	1.5876

The combination of sensors [1, 2] gives a placement index of 2.9999 out of 3. Therefore, by only measuring at node 5 in directions *x* and *y* provides with the best combination to capture the first three modes shapes.

6. STUDIED STRUCTURE

6.1. Sensor placement

A mathematical model of building 4p was constructed (see figure 4). This consists of 72 nodes and 135 elements (54 columns and 81 beams). Nine mode shapes were use as targeted modes.

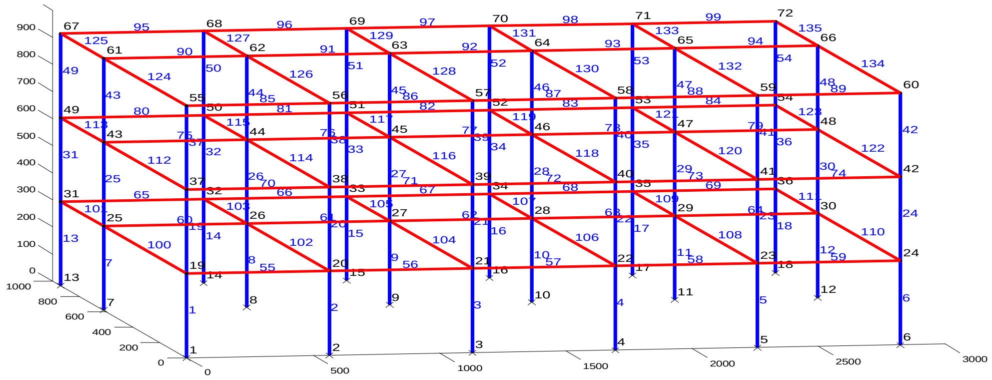


Figure 4. Model of building 4p

The sensors with the largest importance index are shown in figure 5. The combine value for these sensors is 4.204 out of 9 possible. Nodes 61 and 55, in the transversal and longitudinal directions respectively, provide with a combine index placement of 1.273.

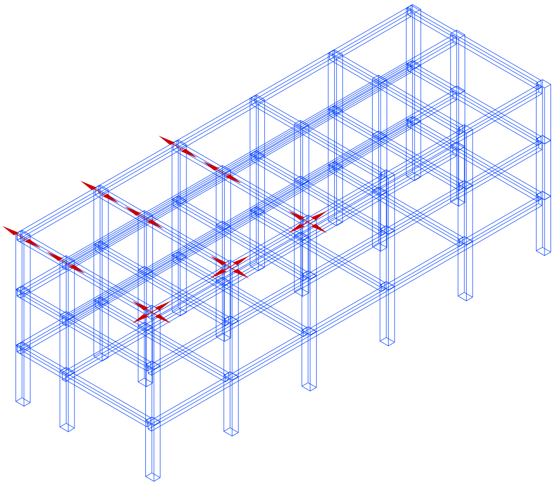


Figure 5. Optimized sensor placements for 4p building

6.2. Data analysis techniques

6.2.1. Fast Fourier Transform

One of the most common data analyses is to find the frequency content in the signal. There are several techniques, among them the most popular is the fast Fourier transform (Bendat and Piersol 1986).

$$\ddot{X}(f) = \int_0^T \ddot{x}(t)e^{2\pi i f t}\,dt \qquad (6.1)$$

In which $\ddot{x}(t)$ is the acceleration and $\ddot{X}(f)$ is its Fourier transform.

6.2.1. Natural Excitation Technique and Eigensystem Realization Algorithm (NExT-ERA).

The Eigensystem Realization Algorithm (ERA) was developed by Juang and Pappa in 1985. There has been broadly used in the system identification of structures. However, this methodology requires an of impulse response of the structure in order to capture the dynamic characteristics of the system. The Natural Excitation Technique (NExT) could, from random vibration, obtain the response impulse of the system (James et al 1993). This technique was used in this study and, for space reasons; only results from the analysis are presented.

6.3. Instrumentation

The instrumentation of the 4p building was done using two different systems: wire and wireless. The first system was comprised by 4 PCB accelerometers. The measurements consisted in 24 records of 5 minutes of length. All of the records were done at the roof of the structure.

The wireless instrumentation was done using 4 Imote2 using the SHM-A sensor board (Illinois Structural Health Monitoring Project 2009). In particular this sensor board has a tri-axial accelerometer. As well as for the wire system 24 measurements were done of 5 minutes of length. In figures 6 and 7 are presented a typical accelerogram obtain from each system

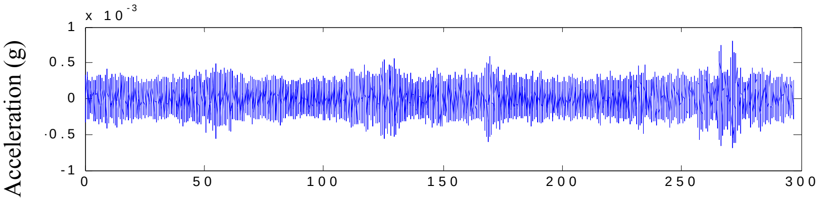


Figure 6. Typical wired record

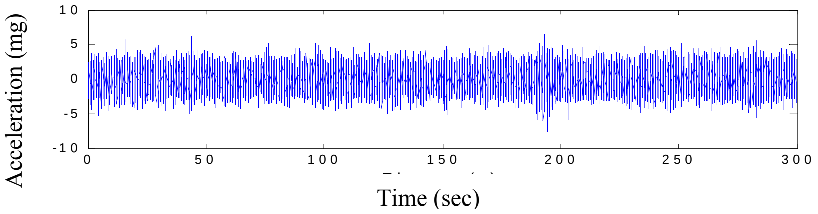


Figure 7. Typical wireless record

6.4. Results

6.4.1. Wired instrumentation

Fourier spectrums were calculated form the measurements recorded. Figure 8 present a typical plot obtained. It can be clearly appreciated a high frequency content at 3.375Hz and 4.688 Hz. A summary of the results is presented in table 5.

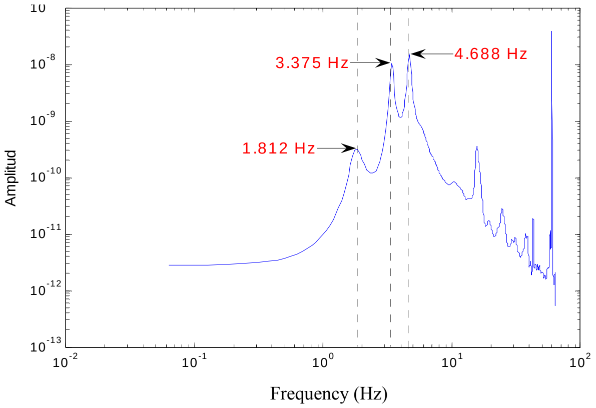


Figure 8. Typical Fourier graph for the wired instrumentation

Also, from the records the NExT-ERA methodology was applied. The first frequencies and mode shapes were identified. A summary of the results are presented in table 6

6.4.2. Wireless instrumentation

Fourier spectrums were calculated form the measurements recorded. Figure 9 present a typical plot obtained. It can be clearly appreciated a high frequency content at 3.418 Hz and 4.59 Hz. A summary of the results is presented in table 5.

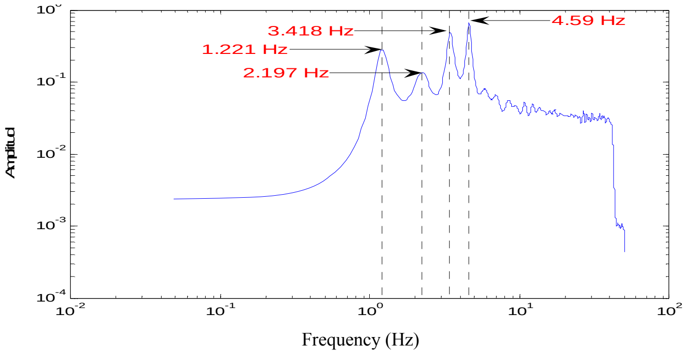


Figure 9. Typical Fourier graph for the wireless instrumentation

Also, from the records the NExT-ERA methodology was applied. The first frequencies and mode shapes were identified. A summary of the results are presented in table 6.

6.4.1. Summary

Table 5 presents the natural periods identified by the Fourier analysis.

Table 5. Natural periods identified by Fourier analysis

Wire instrumentation				
	Mode 1	Mode 2	Mode 3	Mode 4
Media	0.293	0.211	0.180	0.152
σ	0.0069	0.0034	0.0074	0.0032
C.V	0.0233	0.0163	0.0408	0.0211

Wireless instrumentation				
	Mode 1	Mode 2	Mode 3	Mode 4
Media	0.305	0.222	0.179	0.152
σ	0.0175	0.0142	0.0040	0.0053
C.V	0.0557	0.0633	0.0226	0.0349

The values obtained for both of the systems have a good agreement. However, the wireless system has higher standard deviation (σ) and coefficient of variation (CV).

Table 6 presents a summary of the natural period identified by the NExT-ERA methodology.

Table 6. Natural periods identified by NExT-ERA

Wire instrumentation						
Record	Mode 1	MAC	Mode 2	MAC	Mode 3	MAC
1	0.283	0.940			0.190	0.887
2	0.262	0.979				
3			0.217	0.975		
4			0.207	0.957		
Average	0.295		0.209		0.181	0.295

Wireless instrumentation						
Record	Mode 1	MAC	Mode 2	MAC	Mode 3	MAC
1	0.272	0.933			0.183	0.930
2	0.283	0.946				
3			0.225	0.983		
4			0.219	0.846		
Average	0.315		0.224		0.179	0.315

The values of the Modal Assurance Criterion (MAC), that is a scalar that relates the relationship between two modal vectors, have values close to the unity. The values obtained from the Fourier analysis and NExT-ERA are similar.

7. CONCLUSIONS

The sensor placement methodology used in this paper required to set a number of targeted mode shapes beforehand. In general, the first 5 modes of a given structure will represent more than 85% of the modal participation factor. In case of having a particular interest on a specific mode then the sensors placement will have a different arrangement. The contribution of rotation degrees of freedom can be ignored. These have a small participation in the determination of first mode shapes. Probably for local modes these degrees of freedom should be taking in account.

The dynamic characterization results from the wire instrumentation are less disperses than the wireless sensors. The coefficients of variations have lower values. This may be due to the technological disadvantages of the sensors such as the limited digital analog conversion, as well as lower sensitivity of the sensors.

A traditional Fourier spectrum analysis can help to determine with a certain level of accuracy the natural frequencies of the structure. This method should include a stabilization diagram to objectively choose the identified frequencies.

The NExT-ERA method identifies in a practical and objective manner the natural frequencies of the structure. The MAC is reliable discriminator for the selection of the identified modes.

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