WIRELESS NETWORK MONITORING SYSTEM FOR CULTURAL HERITAGE BUILDINGS

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Abstract

This paper focuses on the use of wireless sensors networks (WSN) on cultural heritage buildings for long-term monitoring purposes. This technology is highly attractive because of both the reduced dimensions of the sensors and the absence of cables, that ensures a small visual impact. In this way, the need of a long-term monitoring is addressed without significant impact on the features of the cultural heritage. Nevertheless, this technology is still growing, and several issues still need to be addressed: wireless connection of signals is not even simple because of the thickness of the structural elements, size of the transmitted packages could not be too large, thus implying low frequency resolution and small length signals, etc.[1] [2].

In this emerging scenario, this paper discusses and reports on an automated procedure setting-up for the Modal Tracking (MT) of the Modal Parameters (MP) obtained from long-term monitoring data. The considered data were recorded through a WSN recently installed on a representative historic structure: an ancient masonry tower [3]. The monitoring system has been built with cheap devices, ensuring a wide applicability to the cultural heritage. As shown by several authors [4] [5], the tracking of the frequency across a suitable time span allows to identify possible structural anomalies and/or checking the effectiveness of a specific retrofitting. The results of the first six months are discussed in detail, showing performances and criticism of the monitoring system.

INTRODUCTION

The preservation of the Cultural Heritage (CH) is one of the biggest challenges for our generation to avoid the loss of priceless objects. The recent cases of partial or total collapses renewed the attention on that, topic showing how that structures that are exposed to hazardous events.

The Structural Health Monitoring (SHM) framework gives a powerful tool to analyze the evolution in time of the selected damage sensitive features. That operation, usually known as Modal Tracking (MT), is based on extraction of the Modal Parameters (MP) through an automated procedure. The major part of the automated procedure proposed in the last years are based on the Stochastic Subspace Identification algorithm [6], fed both with the data or with the covariance matrix. The capability of the technique in the modal identification under unknown input in operative conditions led to an increasing interest among the scientific community. The main issue was the high number of setting parameters needed for perform the modal identification. Indeed, in several works the Authors [7–10] proposed several semi or fully automated procedures based on the clustering analysis techniques.

Then the identified modes are tracked [11,12] over the time based on the distance in terms of frequency and Modal Assurance Criterion (MAC) index.

The most investigated damage sensitive feature is the frequency because of its numerical stability and for the limited number of accelerometers required for the identification. Even if the frequency is sensitive to the environmental effects such as temperature and humidity [13–15] that can be of the same measure of that produced by a damage. Then the environmental effects are compensated by ARX model, Multiple Linear Regression (MLR), the Principal Component Analysis (PCA) and the non linear models as the kernel PCA. The damage detection is then finalized through statistical tools called control charts [16].

In the recent years, many Authors [4,17] developed monitoring systems for the CH site, showing how the detection of damage can be successfully achieved with a limited number of accelerometers.

In the present paper is introduced an algorithm for the features extraction in the continuous dynamic monitoring system installed on a historic masonry tower from the recorded signals. The entire monitoring system is wireless, and the accelerometers are Micro Electro Mechanical Systems (MEMS) devices. Not so many cases of application of wireless long-term monitoring system to the CH, despite the advantages in terms of low invasiveness.

The results of the first six months of monitoring of an ancient masonry tower through a continuous (ten minutes of record every hour) wireless monitoring system and the features extraction algorithm are showed.

THE FEATURES EXTRACTION ALGORITHM

The Modal Parameter Identification (MPI) through automated procedures is still an open issue. The parametric techniques in the time allows the implementation of codes based on the identification of the system properties managing the data collected by the sensors. The calibration of the procedure allowing to distinguish among the real modes and the mathematical or spurious modes minimizing the variance of the identified modal parameters is one of the biggest issues that usually is underestimated.

Nevertheless, in the operative conditions the source of excitation is sometimes a colored noise or a harmonic excitation and the hypothesis of a broadband process decays. In many cases the signals exhibit a low power respect to the ground noise leading to difficult modal identification. Considering all these problems the automated procedure should replace the judgment of an expertise selecting the recorded signals which lead to a higher accuracy in the identification of the MP. This procedure is effective if the monitoring system collect a high number of records for each day, enabling the Continuous Vibration-Based Structural Health Monitoring (CVB-SHM). Ceravolo [18] applied the CVB-SHM technique to a complex elliptical dome by selecting the input of the identification procedures exhibiting higher levels of root mean square. Then the Subspace-Stochastic Identification based on the data (SSI-data) is set guaranteeing the identification of a higher number of modes.

The algorithm herein proposed is based on the definition of statistical threshold through the analysis over a limited period (Calibration Phase) that affect all the phases of the automated procedure. Starting from the selection of the inputs, the setup of the modal order and the number of rows in the Henkel matrix and the definition of the threshold for each mode for the MT are set.

The input selection is based on the quality of the signals measured through the kurtosis and the rms and on the level of signal respect to noise measured as the signal to noise ratio [19] (SNR). The setup of the SSI based on the covariance matrix of the signal (SSI-cov) is made by means of a sensitivity analysis and then by the analysis of the obtained standard deviations of each mode in terms of frequency and damping ratio. Then the distance in terms of MAC and frequency is evaluated for each mode.

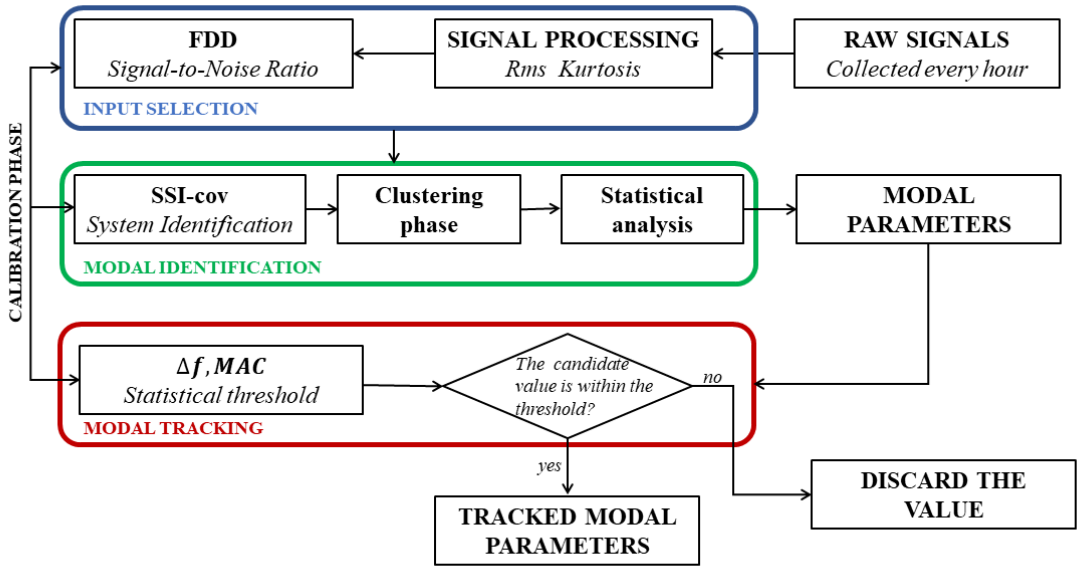


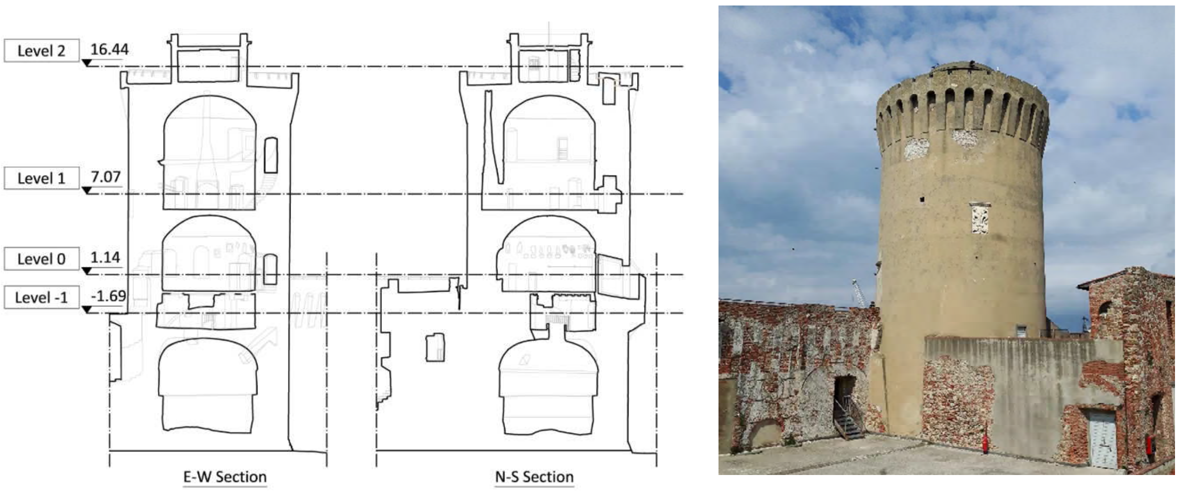
Figure 1: Block scheme of the proposed automated modal identification algorithm.

APPLICATION TO THE MATILDA'S TOWER

The Matilde Tower in the Livorno's harbor, is a round plan tower with a height of about 29 m and an external diameter of about 12 m. The masonry walls have a thickness of about 2,5 m with a spiral staircase embedded to connect the level zero with the upper two levels. The tower has four levels mainly built by vaults that were reinforced with steel bars in the past centuries. In the upper level there is a round terrace with at the center another small round area with a flat slab.

The tower was erected as a free-standing structure probably in the late XII century with the purpose of ensuring a clear observation of the sea and the possibility of repelling the enemy attacks from all directions. With the passing of centuries, the structure was surrounded by the walls, becoming a complex fortress (the Old Fortress). The whole architectural complex shows a severe cracking pattern, probably due to several causes (foundation settlements, sea erosion, bombing of the second world war).

Within the MOSCARDO project, a research project funded by Tuscany Regional Administration in 2015-2018, the tower was listed in the relevant cases of study to analyze to develop a wireless monitoring system and a reliable post-processing algorithm. Indeed, the modal properties of the structure were extracted from preliminary dynamic tests [3]. The results of the preliminary dynamic tests campaign were also very useful to understand the characteristics of the dynamic excitations and their intensity levels. In the preliminary experimental campaign, the most relevant dynamic loads were the wind and the harmonic forces probably generated by the engines of the boats operating in the harbor.



(a)

(b)

Figure 2 (a) cross sections of the Matilda’s tower. (b) Global view from inside the Old Fortress of the Matilde Tower in Livorno.

The monitoring system and the calibration of the MP extraction algorithm

The wireless sensor network installed on the tower is composed by seven MEMS accelerometers (three at the level 0 and four at the terrace level), two meteorological stations measuring the temperature and humidity (one inside the level 0 and one outside at the terrace level), one anemometer (at the top of the highest level) and two strain gauges on the steel chains of the level 0. The acquisition last for ten minutes for every daily hour with a frequency of acquisition of 50 Hz, the data are then sent to a server and the results can be visualized on the website (*http://www.moscardo.it/*).

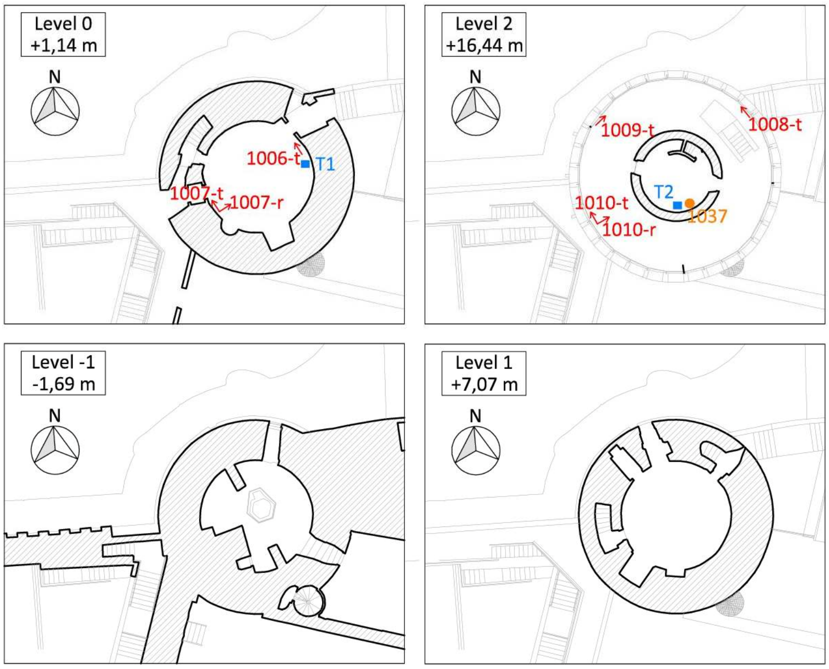


Figure 3 The sensor positions for the long-term monitoring of the Matilde Tower. The red arrows represent the direction of the accelerometers. In blue are represented the two meteorological stations (temperature and humidity). In yellow the anemometer measuring the wind speed and direction.

(a) (b) (c)

Figure 4 (a) The biaxial accelerometer at the node 1007. (b) The node 1037 with the anemometer and the meteorological station. (c) A node of the network at the level zero with the meteorological station a monoaxial accelerometer and the gateway.

The calibration of the algorithm is made over two distinct periods of one week. The first period #P1 (3/12/2018-7/12/2018) is when the tower is excited by the highest wind level and the second #P2 (15/02/2019-22/02/2019).

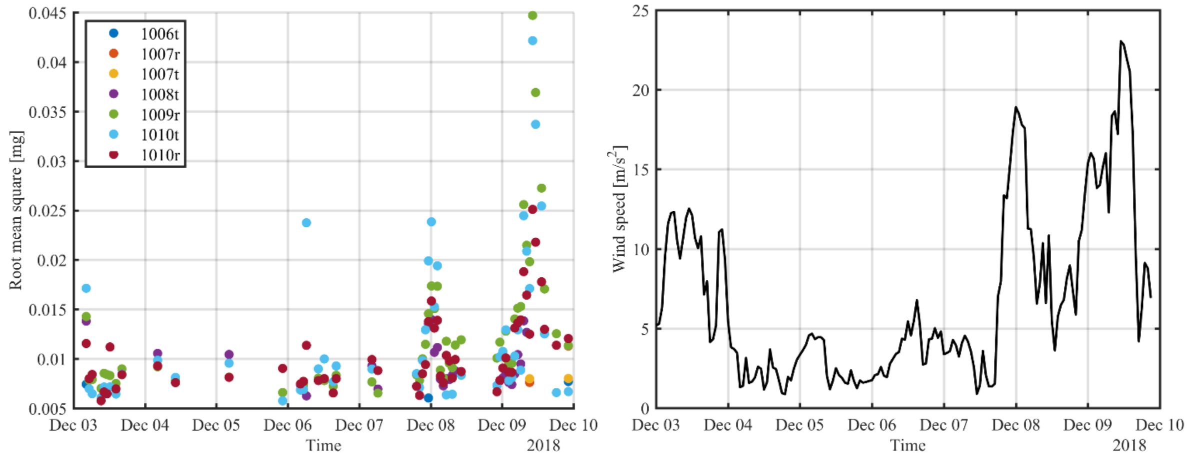


Figure 5 The results of the first calibration period (#P1) in terms of rms and average wind speed.

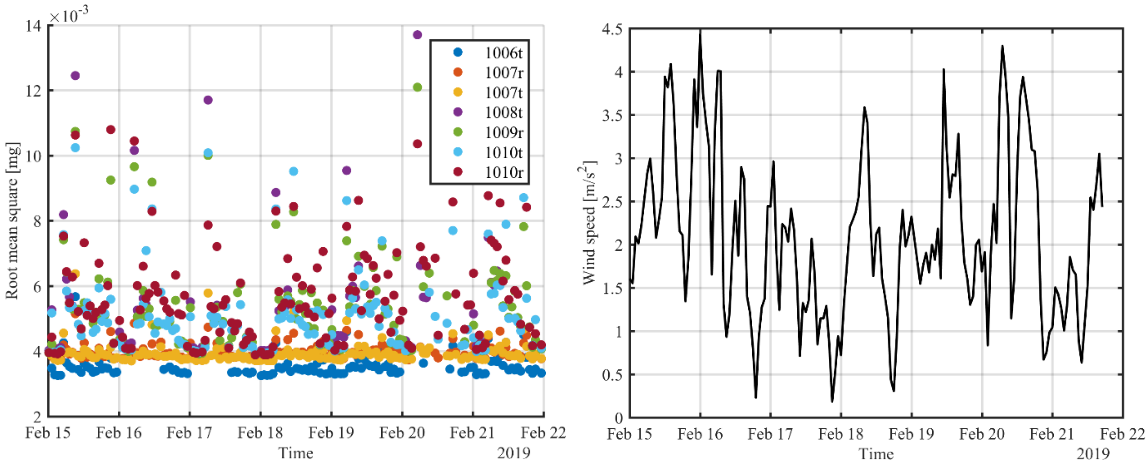


Figure 6 The results of the second calibration period (#P2) in terms of rms and average wind speed.

From the analysis of these two extreme events the threshold for the input selection are defined by means of an outlier analysis excluding the values outside 1,5 times the interquartile range. Then the minimum values evaluated from the two periods is selected in terms of rms and SNR and the maximum for the Kurtosis. Indeed, the first two thresholds guarantee a minimum input quality even if the external excitation is very low. Instead the Kurtosis gives a refined information about the tails of the pdf that can from anomalies in the signals or from non-gaussian process.

Table 1: Threshold values for the input selection

	SNR [dB]	**RMS [mg]**	**Kurtosis**
#P1	39,06	0,0075	118,67
#P2	34,72	0,0040	24,49
Threshold	34,72	0,0040	118,67

In the analysed case of study in the band of interest (0-10 Hz) are available the first three modes, that in many cases are not excited at the same time. The automated procedure for the modal identification based on the *SSI-cov* algorithm is set by means of a sensitivity analysis and a minimum number of elements for each cluster is chosen to avoid the selection of spurious and mathematical modes. In the calibration period it is evaluated the complexity of the mode shapes by means of the Mean Phase Deviation (MPD) and Mean Phase Collinearity (MPC) [20]. Both these indicators are normalized to give a result equal to one for perfect real modes and equal to zero for modes with the highest degree of complexity. Usually the physical modes exhibit a low degree of complexity, but in some cases some degree of complexity can arise from the structural non-linear behaviour [21]. For these reasons a statistical threshold is built for each mode in terms of MPC and MPD as the minimum value of the mean across the two calibration periods.

Table 2: Threshold values for the modal identification phase.

	MPC	**MPD**
#P1	0,90	0,77
#P2	0,73	0,78
Threshold	0,73	0,77

The MT of the identified modal parameters is made starting from a reference value for each mode in terms of frequency and mode shapes. During the calibration phase a hierarchical clustering algorithm is performed with two initial fixed threshold 5 % for the frequency and 0,7 for the MAC index. Then for each identified mode is computed the MAC distance for each value and the threshold value is obtained as the lower bound of the interquartile range. Then the maximum value among the two calibration periods is chosen for the MT of each mode during the whole monitoring period.

Table 3: Threshold values for the MT of the MP

	1st Mode	**2nd Mode**	**3rd Mode**
#P1	0,78	0,79	0,84
#P2	0,73	0,79	-
Threshold	0,78	0,79	0,84

This conservative choice is made to avoid the selection of some harmonic response of the structure near to the band of interest of each modal frequency.

The results of the first six months

The early results from the first six months (from the 19th of September 2018 to the 20th of March 2019) of long-term monitoring of the Matilda's tower obtained with the algorithm introduced in the previous section are described herein.

Despite some disconnections of instruments due to the initial trial period, the results can furnish some preliminary information on the working activity of the package WSN monitoring system and the feature extraction algorithm. The MT of the first three modes is successfully achieved, even if some offline periods (mid-November and mid-January) of some sensors cannot allow a continuous tracking over the monitoring period.

The first two modes seem to be less scattered than the third, implying a lower accuracy in the modal identification. Moreover, the third mode cannot be identified in every session, probably requiring higher energy levels in the input.

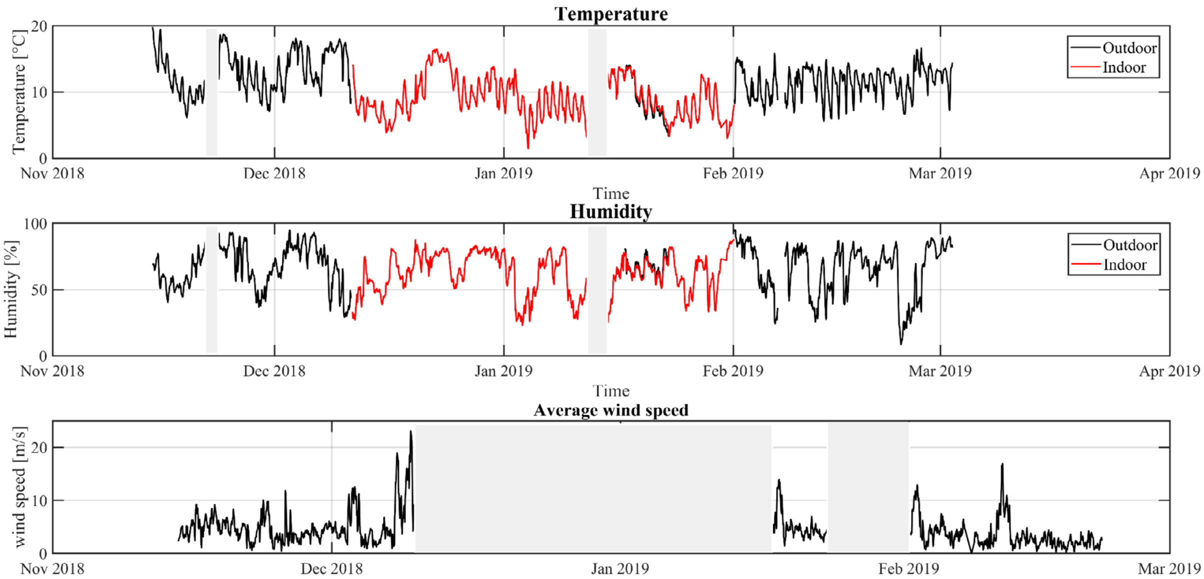


Figure 7 The variation of the environmental parameters in the first six months of monitoring period.

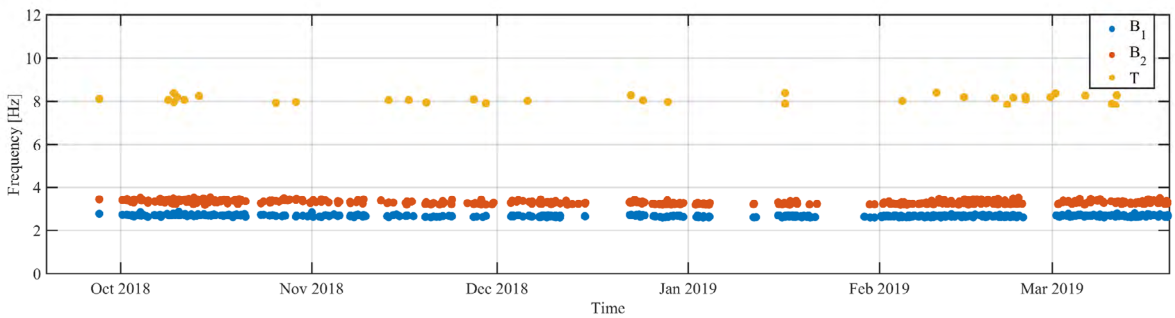


Figure 8 The modal tracking of the first three modes: The bending (B_1, B_2) and the torsional (T).

CONCLUSIVE REMARKS

The presented monitoring system is based on a wireless network of sensors developed during the MOSCARDO project shows how it is possible to satisfying the requirements of low visual impact and low costs that are fundamental in the CH application.

The feature extraction algorithm for a CVB-SHM monitoring system is presented focusing on the calibration of the entire automated procedure to obtain good quality identification results that is crucial for the systems based on the tracking of the frequency. Enabling the damage detection (level 1 in the Rytter's scale [22]) for the monitored CH building.

Despite the presented algorithm is suitable for every kind of CH building, the preliminary dynamic identification and the calibration phase should be adopted to the operative conditions and to the dynamics of the monitored structure.

In the case of study presented herein the main dynamic excitation source was the wind, and the

calibration phases furnishes the input selection parameters in order to avoid outliers or low excited modes. In the modal identification phase through an automated *SSI-cov* procedure with the initial values are set by means of a sensitivity analysis. Then for the MT the MAC thresholds are defined for each mode by the results obtained in the calibration period. Instead the distance in terms of frequency is fixed relatively high to group together the MP represented the same mode with different environmental conditions.
To make further analysis, more data are required with different environmental conditions to understand the relationships among these values and the tracked modes.

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REFERENCES

[1] A. Pierdicca, F. Clementi, D. Isidori, E. Concettoni, C. Cristalli, S. Lenci, Numerical model upgrading of a historical masonry palace monitored with a wireless sensor network, *Int. J. Mason. Res. Innov.* **1** (2016) 74–98.
[2] F. Potenza, F. Federici, M. Lepidi, V. Gattulli, F. Graziosi, A. Colarieti, Long-term structural monitoring of the damaged Basilica S. Maria di Collemaggio through a low-cost wireless sensor network, *J. Civ. Struct. Heal. Monit.* **5** (2015) 655–676.
[3] G. Zini, M. Betti, G. Bartoli, S. Chiostrini, Frequency vs time domain identification of heritage structures, *Procedia Struct. Integr.* (2018).
[4] N. Cavalagli, G. Comanducci, C. Gentile, M. Guidobaldi, A. Saisi, F. Ubertini, Detecting earthquake-induced damage in historic masonry towers using continuously monitored dynamic response-only data, *Procedia Eng.* **199** (2017) 3416–3421.
[5] F. Lorenzoni, F. Casarin, C. Modena, M. Caldon, K. Islami, F. da Porto, Structural health monitoring of the Roman Arena of Verona, Italy, *J. Civ. Struct. Heal. Monit.* **3** (2013) 227–246.
[6] B. Peeters, G. De Roeck, Stochastic System Identification for Operational Modal Analysis: A Review, *J. Dyn. Syst. Meas. Control.* **123** (2001) 659.
[7] F. Magalhães, Á. Cunha, E. Caetano, Online automatic identification of the modal parameters of a long span arch bridge, *Mech. Syst. Signal Process.* **23** (2009) 316–329.
[8] F. Ubertini, C. Gentile, A.L. Materazzi, Automated modal identification in operational conditions and its application to bridges, *Eng. Struct.* **46** (2013) 264–278.
[9] E. Reynders, J. Houbrechts, G. De Roeck, Fully automated (operational) modal analysis, *Mech. Syst. Signal Process.* **29** (2012) 228–250.
[10] E. Neu, F. Janser, A.A. Khatibi, A.C. Orifici, Fully Automated Operational Modal Analysis using multi-stage clustering, *Mech. Syst. Signal Process.* **84** (2017) 308–323.
[11] P. Verboven, E. Parloo, P. Guillaume, M. Van Overmeiere, Autonomous Structural Health Monitoring--Part I: Modal Parameter Estimation and Tracking, *Mech. Syst. Signal Process.* **16** (2002) 637–657.
[12] A. Cabboi, F. Magalhães, C. Gentile, Á. Cunha, Automated modal identification and tracking: Application to an iron arch bridge, *Struct. Control Heal. Monit.* **24** (2017).
[13] L.F. Ramos, L. Marques, P.B. Lourenço, G. De Roeck, A. Campos-Costa, J. Roque,