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A vibration-based health monitoring program for a large and seismically vulnerable masonry dome

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Abstract. Vibration-based health monitoring of monumental structures must rely on efficient and, as far as possible, automatic modal analysis procedures. Relatively low excitation energy provided by traffic, wind and other sources is usually sufficient to detect structural changes, as those produced by earthquakes and extreme events. Above all, in-operation modal analysis is a non-invasive diagnostic technique that can support optimal strategies for the preservation of architectural heritage, especially if complemented by model-driven procedures. In this paper, the preliminary steps towards a fully automated vibration-based monitoring of the world's largest masonry oval dome (internal axes of 37.23 by 24.89 m) are presented. More specifically, the paper reports on signal treatment operations conducted to set up the permanent dynamic monitoring system of the dome and to realise a robust automatic identification procedure. Preliminary considerations on the effects of temperature on dynamic parameters are finally reported.

1. Introduction

Historic masonry monuments accumulate damage during their lifetime due to materials deterioration, repeated loads and exceptional events such as earthquakes. Therefore, repairs and strengthening interventions are necessary over time to preserve these monuments. Structural Health Monitoring (SHM) can help in planning maintenance activities and in assessing the effectiveness of interventions and the overall safety levels of historical buildings [1][2][3]. Among these, SHM procedures based on global vibration measurements are particularly advantageous because the dynamic response of a structure reflects its global state. Specifically, vibration-based SHM based on Operational Modal Analysis (OMA) procedures are optimal monitoring tools for heritage buildings because of their non-invasiveness. The dependence of the dynamic parameters, i.e. frequencies, modal shapes and damping, on the health state of a building has been investigated and demonstrated in several studies [4][5]. However, the use of these parameters as a damage indicator is still deemed a complex operation because of their variability under environmental conditions. The environmental factors that typically influence the values assumed by the dynamic parameters are temperature, humidity and rain [6][7][8][9], excluding the variability from excitation characteristics. Therefore, the effects of the environmental factors must be investigated. More specifically, any custom-designed SHM procedure requires the preliminary definition of the environmental variations of the dynamic parameters. Changes in the state of a building, indeed, should be related to anomalous deviations of the dynamic parameters rather than to daily or seasonal variations. To this aim, statistical recurrence of the characteristics of the parameters extracted from data recorded during several environmental conditions must be determined.

This paper proposes a protocol to automatically perform OMA on monumental buildings. The protocol is developed using the data acquired by the dynamic monitoring system installed on the dome of the Regina Montis Regalis Basilica (Piedmont, Italy), the world's largest masonry oval dome (internal axes of 37.23 by 24.89 m). As a first step, some aspects connected with the data acquisition are discussed. Secondly, a procedure to discriminate the main modes of the structure is established. Finally, some conclusions about the effect of temperature on the dynamic parameters are drawn, using the data acquired from November 21, 2016 to January 21, 2017.

2. The Regina Montis Regalis Basilica

Regina Montis Regalis Basilica is a monumental building and represents a significant historical architecture of the Italian Cultural Heritage owing its magnificent and impressive masonry dome that, with the internal axes of 37.23 by 24.89 meters, is the world's largest oval dome [10], ‘figures 1(a,b)’. The construction began in 1596 based on a project of the architect Ascanio Vitozzi, and then the construction was ultimate by architect Francesco Gallo in 1735. Since the first years, several structural problems affected the building because of foundation were built on a clay layer [11]. Cracking phenomena are located especially in the dome-drum area with a total width of up to 416 mm. In 1983, concerns over the structural health state of the building prompted the decision to undertake analysis, monitoring activities and strengthening interventions.

In 1987, an hooping system was put in place, consisting of four closed rings of 56 active steel tie-bars located at the drum level ‘figure 1(c)’and, in the same years, a static monitoring system was installed on the Basilica. It consists of 133 sensors subdivided in two groups: instruments to measure strains, stresses and cracks and instruments to measure the boundary conditions.

Figure 1. (a) Regina Montis Regalis Basilica; (b) The Basilica dome; (c) The strengthening system installed in 1987.

During the last decades, several non-destructive survey campaigns were conducted to better understand the structural behaviour of the Basilica [12]. In 2008, a dynamic identification campaign taken place and data were analysed by the Politecnico di Torino [13], then, preliminary analysis were conducted on the FE model of the structure [14]. The more recent studies consist in the analysis of the static monitoring data acquired in the decade 2004-2014. The analysis prove the stability of the cracks opening and, therefore, the effectiveness of the strengthening system put in place in 1987 [15]. However, the static monitoring system only provides local information about the health state of the Basilica. Consequently, in December 2015, a permanent dynamic monitoring system was installed, in order to investigate global phenomena affecting the structure.

The portion of the building interested by dynamic monitoring activities is the lantern-dome-drum system. Sensor positions were defined through Optimal Sensor Placement (OSP) techniques [16]. OSP procedures used a genetic algorithm to find the best set of instrument positions, referring to the Modal Assurance Criterion (MAC) matrix applied to a dynamically calibrated F.E. model [17]. The permanent dynamic system is composed of 12 mono-axial piezoelectric accelerometers (1000 mV/g; measure range: ± 5 g pk; broadband resolution: 0,00001 g rms; frequency range: (± 5%) 0,5<f<200Hz, (±10%) 0,3<f<4000Hz; resonance frequency: ≥ 10 kHz; temperature range: -65<T<121°C). As shows in ‘figure 2’, three orthogonal accelerometers are located at the base of the crypt to record the ground accelerations. A set of 9 accelerometers are located at different levels in the lantern-dome-drum area, along the longitudinal and transverse directions. In more details: (i) two accelerometers are at the base of the dome at 30 meters height; (ii) two sensors are on the dome at 45 meters height; (iii) one vertical accelerometer is located at the base of the lantern at 50 meters height; (iv) the last three accelerometers are located at the top of the lantern. The monitoring system was designed as a Master-Slave acquisition scheme (see ‘figure 2’). More specifically, the data acquired by the sensors on the lantern-dome-drum system converge to the Master central acquisition unit, instead the data recorded by the accelerometers in the crypt are transmitted to the Slave element, and then, to the Master central. This configuration can reduce distortion effects in the signals by limiting the cable length to about 50 meters.

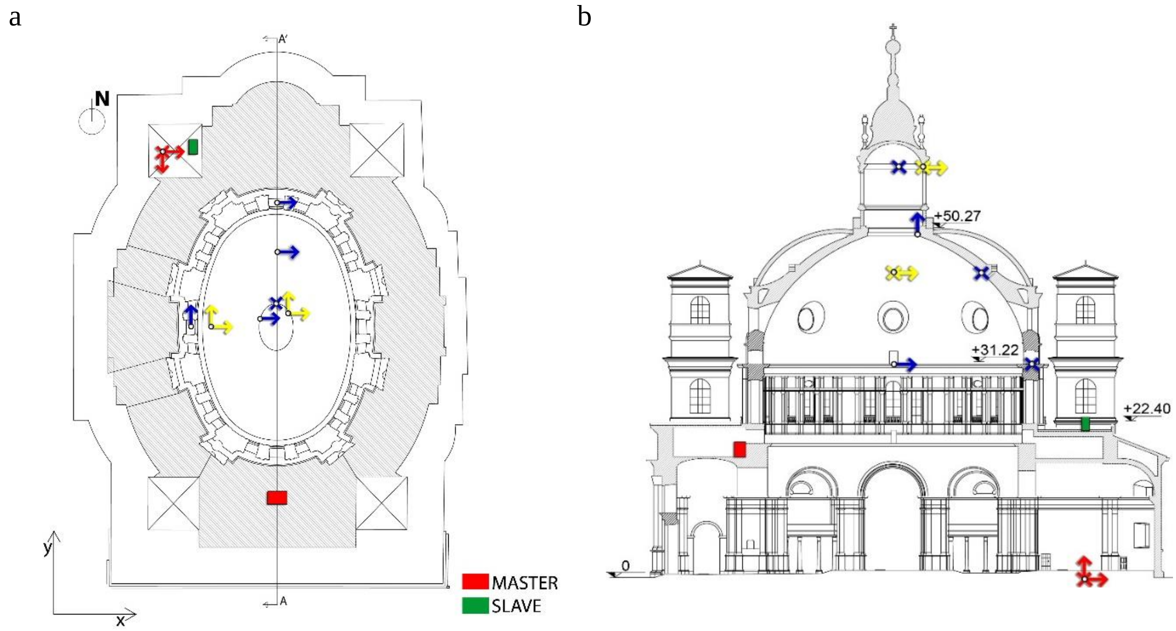

Figure 2. (a) Sensors position in plane; (b) Sensor position in section AA'.

Recorded data are transmitted, through File Transfer Protocol application, both to the Politecnico di Torino and to the Civil Protection Department, since the Basilica has been recently included in the Seismic Observatory of the Structures network owing to its cultural and architectural relevance.

3. Automated identification protocol

The Earthquake Engineering & Dynamics (EED) lab at the Politecnico di Torino is working on a fully automatic experimental modal analysis procedure to assess, in real time, the health state of the Basilica, and to evaluate the possible effects of ground motions. At present, the system identification technique, incorporated in the automatic procedure, consists in a time domain Stochastic Subspace Identification (SSI). More specifically, the third algorithm considered by the unifying theorem of Van Overschee and De Moor [18], often referred to as “canonical variate analysis” (CVA), was used.

The CVA, due to its algebraic nature, the good computational efficacy and its accuracy is adequate to be automatized. Nevertheless, manual preliminary identifications must be performed to set model orders, to perform pre-processing operations of the acquired data, as well as to set the modality of data acquisition. The sampling frequency, the length of the data acquired and its frequency content, respectively, can affect significantly the identification results. As a consequence, the main aim of the manual identification carried out using few signals are to set: (i) the order of the system; (ii) the length of the periodic records; (iii) the pre-processing operations and (iv) the time intervals of data acquisition. The automatic identification procedure was implemented in Matlab® and its efficiency was evaluated by comparing the results of automatic and manual identification sessions. More specifically, the Matlab® code was updated in order to give the same results as the manual identification carried by the operator.

The identification procedure entails a series of data cleansing and pre-processing operations on the signals, such as mean removal, de-trending, decimation, filtering, etc. The dynamic parameters extracted by the SSI, performed on each processed signals, are analysed in terms of stability and regularity. The daily candidate modes are obtained by a clustering analysis performed on the hourly candidate mode and by averaging operations. 'Figure 3' shows the working scheme of the automatic identification procedure and the management of the acquired data. Several database with raw data, post-processed signals, hourly dynamic parameters, daily dynamic parameters and a database of the environmental conditions are created during the automatic identifications. In the following subsections, the different steps of the automatic identification procedure are described in details.

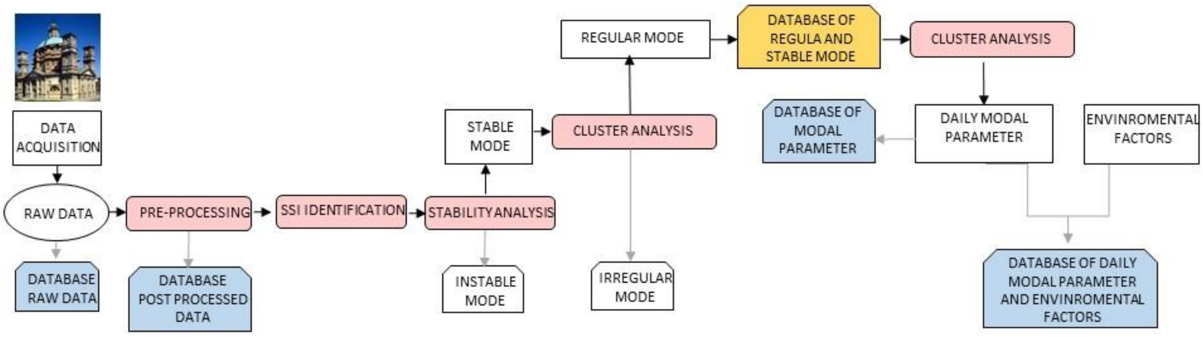

Figure 3. Flowchart of the automatic identification procedure

3.1 Pre-processing

Factors such as sampling frequency, temporal window and frequency content can significantly affect the result of the identification, independently from the model order. As a consequence they must be appropriately set.

For both manual and automated identification of the Basilica, the sampling frequency was set at 100 Hz and kept constant. Conversely, different lengths were used for the identification: 5, 10 and 20 minutes, respectively. The signals of 5 and 10 minutes were obtained by cutting the signal of 20 minutes.

The manual identifications performed evidenced that it is convenient to filter the recorded data in the band 0.5-5 Hz, independently from the length of the signal used. This filtering operation was requested to identify the first two modes, as already detected during the campaign carried out in 2008 [14]. To stress the importance of this filter, 'figure 4' reports the stabilisation diagrams related to the same recorded signal but filtered in the band 0.5-5 Hz and 0.5-15 Hz, respectively.

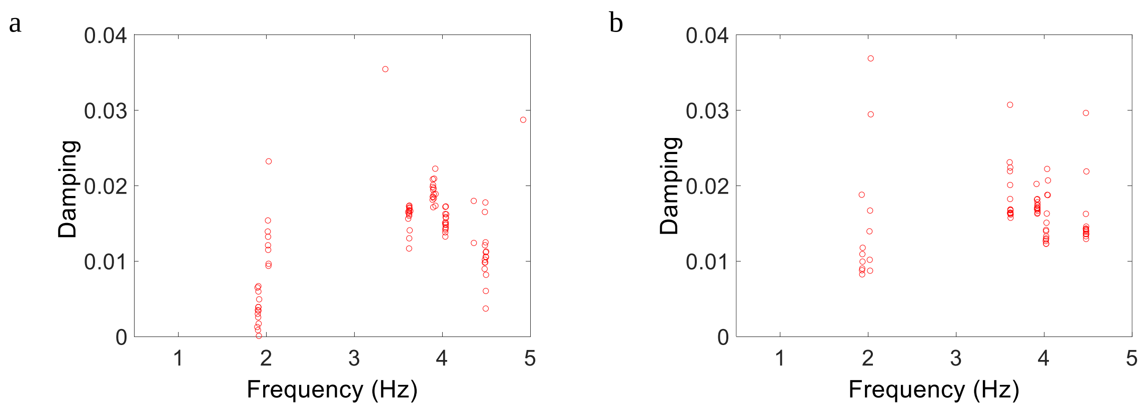

Figure 4. Stabilisation diagram in the range 0.5-5Hz obtained using records of 20 minutes and filtered in the range (a) 0.5-5Hz and (b) 0.5-15 Hz.

At the end of several manual identification sessions, a 20 minutes long signal was chosen for automatic identifications. 'Figure 5' shows the stabilisation diagrams obtained using signals of different lengths, obtained by cutting the same signal of 20 minute. The dotted lines in the diagrams indicate the identified frequencies of the Basilica (see 'Table 1'). The comparison of the stabilisation diagrams shows the difference between the parameters identified using signal of 5 and 10 minute, and some frequencies that are not captured. Furthermore, damping estimates confirms its dependence on the signal segment used in the identification [13].

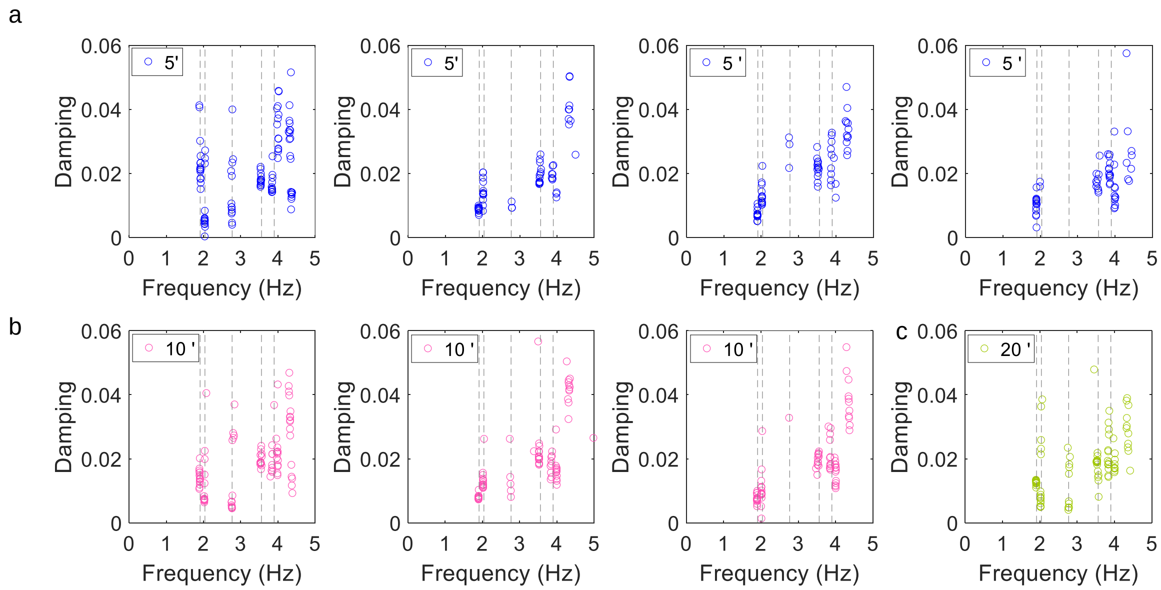

Figure 5. Stabilisation diagram in the range 0.5-5Hz obtained using records of different length, obtained copping the same signal of 20 minute (a) 5 minute signals; (b) 10 minute signal; (c) 20 minute signal.

3.2 SSI identification and stability analysis

The number of the parameters identified will depend on the choice about the SSI model order, whose wrong choice increases the risk to embark spurious modes characterized by a large variability. Despite being eliminated through the stabilisation criteria, spurious modes imply a worthless time-consuming computation. Consequently, a characteristic model order range needs to be chosen to identify the modes of Basilica avoiding worthless computations. To fix this interval, the model order was varied from 30 to 100 during manual identification.

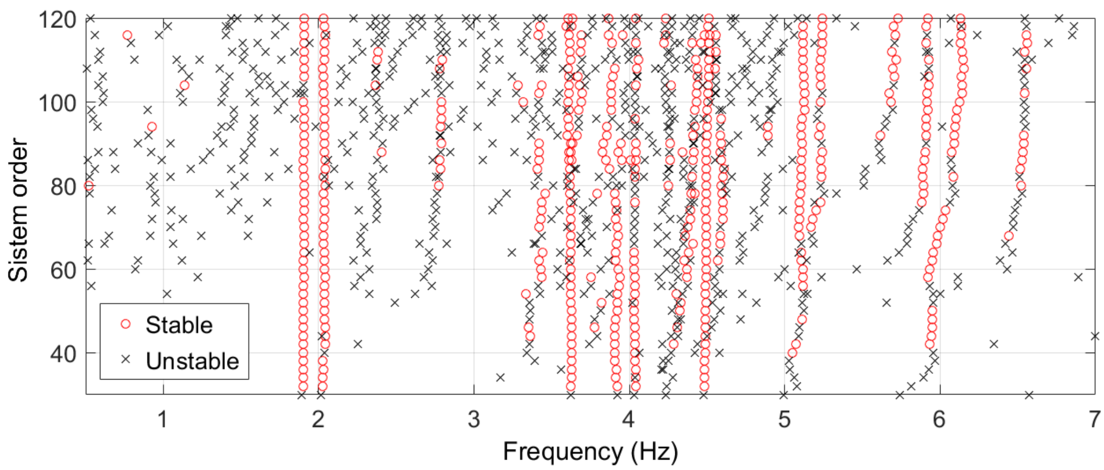

Figure 6. Stabilisation diagram to set the model order of the automated identification procedures.

The stabilisation diagram reported in 'figure 6' shows the uselessness of model orders higher than 60. Indeed, spurious parameters identified for greater model orders, because of their instability, will be removed by the introduction of the following stabilisation criteria: (i) damping in the range 0% - 10%; (ii) damping variation < 2.5 %; (iv) MAC >95%; and (iii) frequency variation < 0.03Hz. The frequency variation was assumed equal to one-third of the variance between the first two frequencies identified in 2008 [14]. Based on these results the model order of the identification algorithm was set to vary in the range 30-60 during the automatic identification

3.3 Clustering analysis and hourly candidate mode

The modes cleared with the stabilisation criteria are investigated in terms of regularity. To do this a clustering analysis is performed and the stable modes are grouped in separate sets belonging to the same structural mode. The number of the cluster is fixed through an iterative procedure considering the mutual distance in terms of frequency and MAC. The reliability of the clusters is assumed as coinciding with their element number and therefore defined through an occurrence index, I_{OCC}, defined as:

$$I_{OCC} = \frac{n}{\left(\frac{N_{max} - N_{min}}{\Delta N}\right)} \tag{1}$$

where n is the numbers of the cluster elements; N_{max} and N_{min} are maximum and minimum order of the SSI model and ΔN is the step model.
The clusters characterised by a value of I smaller than 0.3 are considered irregular and are eliminated. The candidate modes deriving from each signal are obtained as the average of the elements belonging to the same cluster. The weight w_i of i-th element of the cluster is derived by the MAC values through the formula:

$$w_i = \sum_{K=1}^{n} \frac{|\{\Psi_i\}^T\{\Psi_k{}^*\}|^2}{\{\Psi_i\}^T\{\Psi_i{}^*\}\{\Psi_k\}^T\{\Psi_k{}^*\}} \tag{2}$$

where $\{\Psi_i\}$ is the modal shape of the i-th element of the cluster; $\{\Psi_k\}$ are the modal shapes of all the n elements of the cluster.
'Figure 7' overlaps the stable and regular modes identified and the candidate mode defined by Eq. 2, using the data acquired 2 December 2016. The figure shows that the stable identified modes vary over a day. The random variability of frequencies throughout a day, as shown in 'figure 8' for the first frequency, suggests that the daily fluctuations are not related to thermal factors.

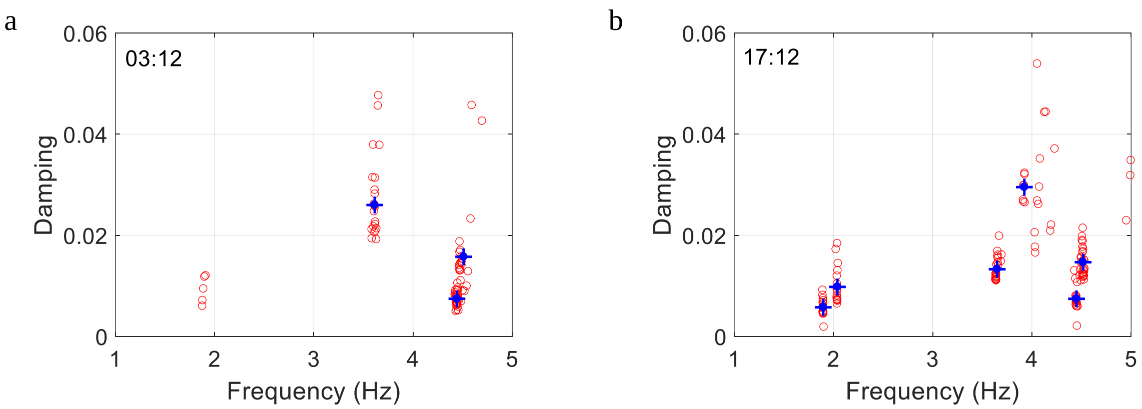

Figure 7. Frequencies identified using data acquired 02/12/2016 at different hours (a) hour 3:12 (b) hour 17:12.

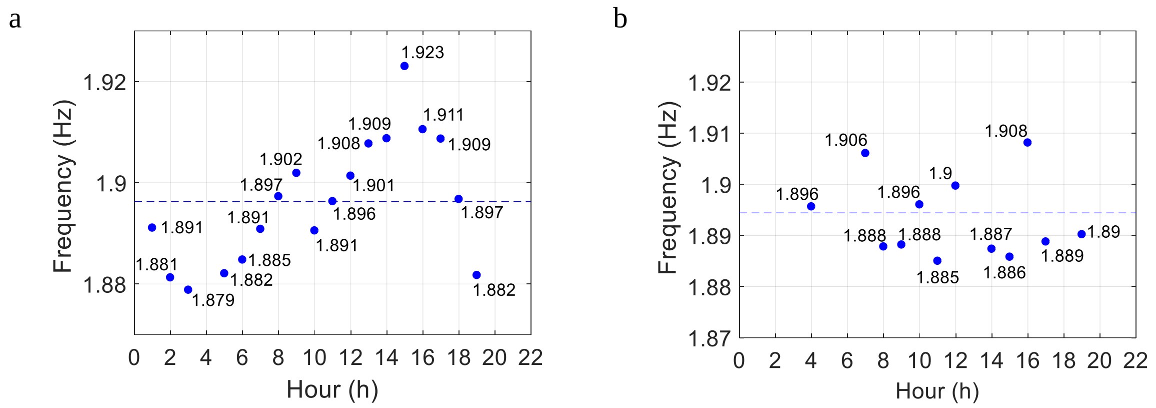

Figure 8. Variability of the first frequency during a day (a) 02/12/2016 (b) 03/12/2016.

'Figure 9' shows that the frequencies identified and their values at the same hours of different days are not constant. Consequently, monitoring should not be based on a single record acquired in the same hour because this would lead to inaccurate conclusions about the state of the Basilica and about the variability of the frequencies with temperature. Based on these results the acquisition system was set to acquire one signal hourly, and a procedure to obtain the Basilica daily candidate modes from the hourly modes was defined.

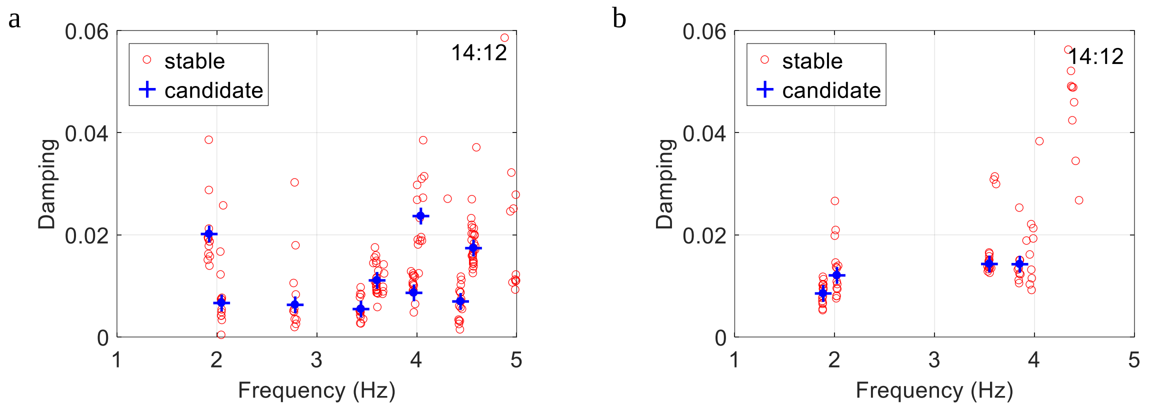

Figure 9. Frequencies identified using data acquired at hour 14:12 on (a) 02/12/2016; (b) 03/12/2016.

3.4 Daily modes from hourly candidate modes

The daily modes are obtained from the hourly candidate modes, through an iterative clustering analysis considering the mutual distance in terms of frequency and MAC. Once the clusters are defined, frequencies and modal shapes of the Basilica are obtained from weighted average operations. The weight of each element depends on its regularity with respect to the cluster and on its occurrence. More specifically the weight of the i-th element of the cluster is defined by:

$$w_i = \left(\sum_{k=1}^{n} \frac{|\{\Psi_i\}^T \{\Psi_k{}^*\}|^2}{\{\Psi_i\}^T \{\Psi_i{}^*\} \{\Psi_k\}^T \{\Psi_k{}^*\}} \right) \cdot \left(\frac{I_{OCC,i}}{\sum_{k=1}^{n} I_{OCC,k}} \right) \quad (3)$$

where $\{\Psi_i\}$ is the modal shape of the i-th hourly candidate mode of the cluster; $\{\Psi_k\}$ are the modal shapes of all the n hourly candidate modes of the cluster; $I_{OCC,i}$ is the occurrence index of the hourly candidate mode, while the $I_{OCC,k}$ is the occurrence index of all the n hourly candidate modes of the cluster. The reliability of the dynamic parameters at the end of the iterative clustering analysis is associated with the sum of the occurrence indices of the hourly candidate mode of the cluster. The dynamic parameters with a high value of I_{OCC} can reasonably be interpreted as structural modes of the

Basilica. Similarly, the parameters with low occurrence can be neglected. The nature of the other dynamic parameters must be investigated with the help of the FE model of the Basilica. 'Figure 10' shows for instance as the number of the daily candidate mode decreases assuming a higher occurrence index.

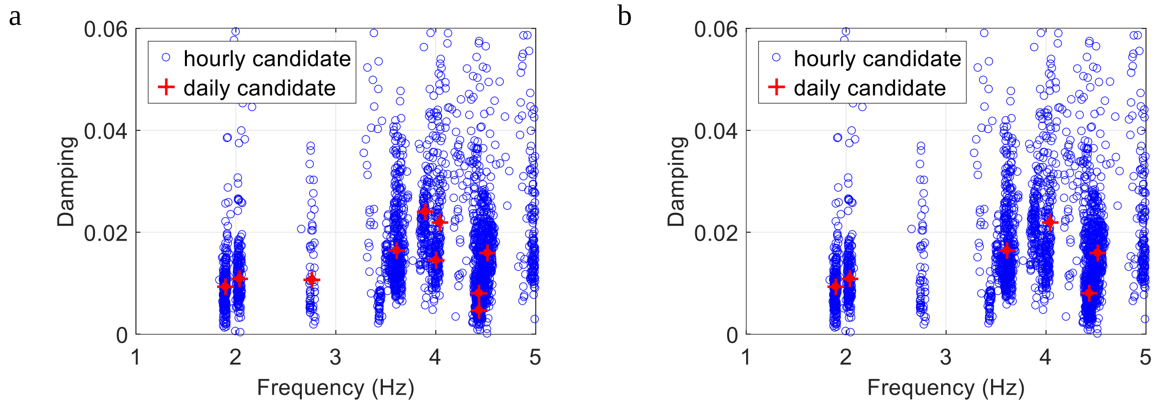

Figure 10. Daily candidate modes in the range 0-5 Hz (02/12/2016) for a minimum occurrence of (a) 50 and (b) 100.

4. Identification results

The above described procedure was used to determine the Basilica dynamic parameters over the period November 2016-January 2017. Environmental factors slightly affect the daily candidate modes that present a reduced variability. Table 1 reports the frequencies of the main modes identified over the aforementioned period. The comparison of these new results with the previous modal identification campaign shows that: (i) the frequencies of the first bending modes of the Basilica are approximately the same. The plots of the modal shapes, as reported in Fig. 11.a and Fig. 11.b, show that the first bending mode at 1.91 Hz has its main component in the Y direction, while the one at 2,04 Hz is a purely X direction bending mode; (ii) the suspect mode detected in 2008 at about 2.86 Hz in the 2008 identification is systematically confirmed in the new identification sessions. This experimental mode, depicted in Fig. 11.d, is associated to the first torsional mode of the whole Basilica's model, being governed by the four bell-towers.

With regards to the plot of the modal shapes, at the drum level there are not enough sensors to capture the torsion of the dome, see Fig. 2; (iii) the second bending modes, along the X and Y direction, respectively, are found at 3.56 Hz and 3.90 Hz, instead of 3.08 and 3.77 Hz.

Table 1. Frequencies identified in 2017.

EXPERIMENTAL 2017 - Freq.(Hz)	Mode classification
1,91	1st bending Y
2,04	1st bending X
2,77	1st torsional Basilica
3,56	2nd bending Y
3,90	2nd bending X
5,13	1st vertical dome

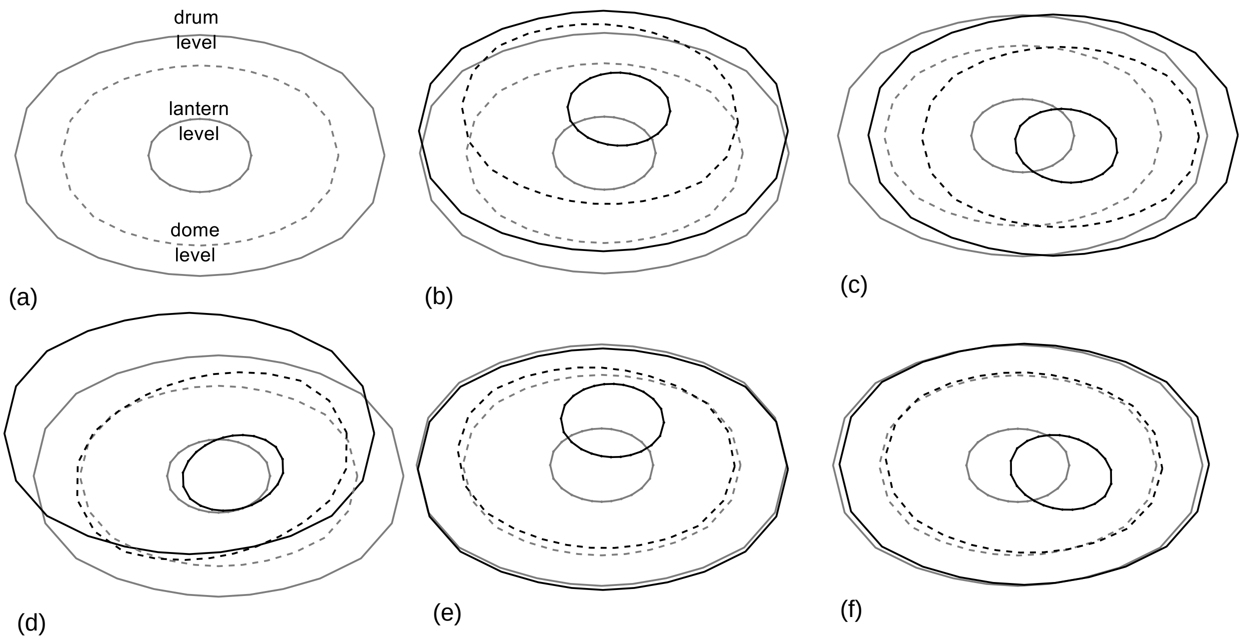

Figure 11. Illustration of the identified modal shapes of: (a) monitored levels of the Basilica (b) the 1st bending mode along Y direction; (c) the 1st bending mode along X direction; (d) the 1st torsional; (e) the 2nd bending mode along Y direction; (f) the 2nd bending mode along X direction.

5. Seasonal variation of frequencies

Assessing the dependence of the dynamic parameters of the Basilica on environmental factor is crucial to activate a robust structural health monitoring. At this stage, the dependence of the first two frequencies on the temperature is investigated. 'Figure 12' combines the frequencies automatically identified with the procedure described above, from 21 November 2016 to 21 January, and the average temperature measured in Vicoforte. Despite the importance of the temperature variation over the investigated period, the duration of this period is too short to draw a general conclusion about the dependence of frequencies on temperature. In any case, the graph seems to suggest the lack of correlation between temperature and the first two frequencies of the Basilica dome.

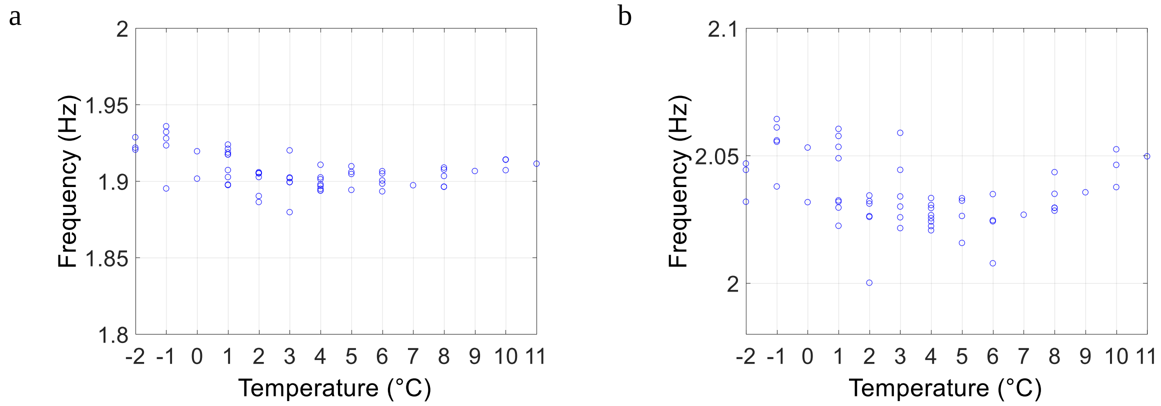

Figure 12. (a) 1st bending mode along Y direction vs. temperature; (b) 1st bending mode along X direction vs. temperature.

6. Conclusions

This paper has described the studies conducted to establish a protocol for the SHM activities to be conducted in the forthcoming years on the Regina Montis Regalis oval dome. The procedure automatically determines the hourly and daily candidate modes, using the signals recorded at each hour.

The identification protocol was defined by comparing different strategies applied to the data acquired by the permanent dynamic monitoring system installed at the beginning of 2016. The next step of this study will correlate the results of the automated identification with the environmental parameters considering a longer period. Quantifying the dependence of the dynamic parameters on environmental factors will be crucial in order to activate a reliable structural heath monitoring and to use dynamic parameters in either data-driven or model-driven SHM procedures.

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