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FIRST RESULTS OF THE VIBRATION-BASED STRUCTURAL HEALTH MONITORING OF A MASONRY DOME

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Abstract. *This paper newly proposes the use of ambient vibration testing, vibration-based continuous dynamic monitoring and automated modal identification for structural assessment of monumental masonry domes. The final purpose of this research is the development of a general methodology for online structural health monitoring of large domes, enabling early detection of damages caused by low return period earthquakes, in a general framework of preventive conservation and heritage resilience. The case study considered here is the dome of the Basilica of Santa Maria degli Angeli in Assisi, recently added to the World Heritage List of Unesco. The basilica is located in the center of Italy and it was built between 1569 and 1679 on the design of the architect Galeazzo Alessi. It consists of a latin cross plan, with 126 m and 65 m dimensions, with a nave, two aisles and a semicircular apse. At the intersection between the transept and nave the building hosts the Porziuncola, a little ancient chapel, symbol of Franciscan spirituality and pilgrims destination since the construction of the basilica.*

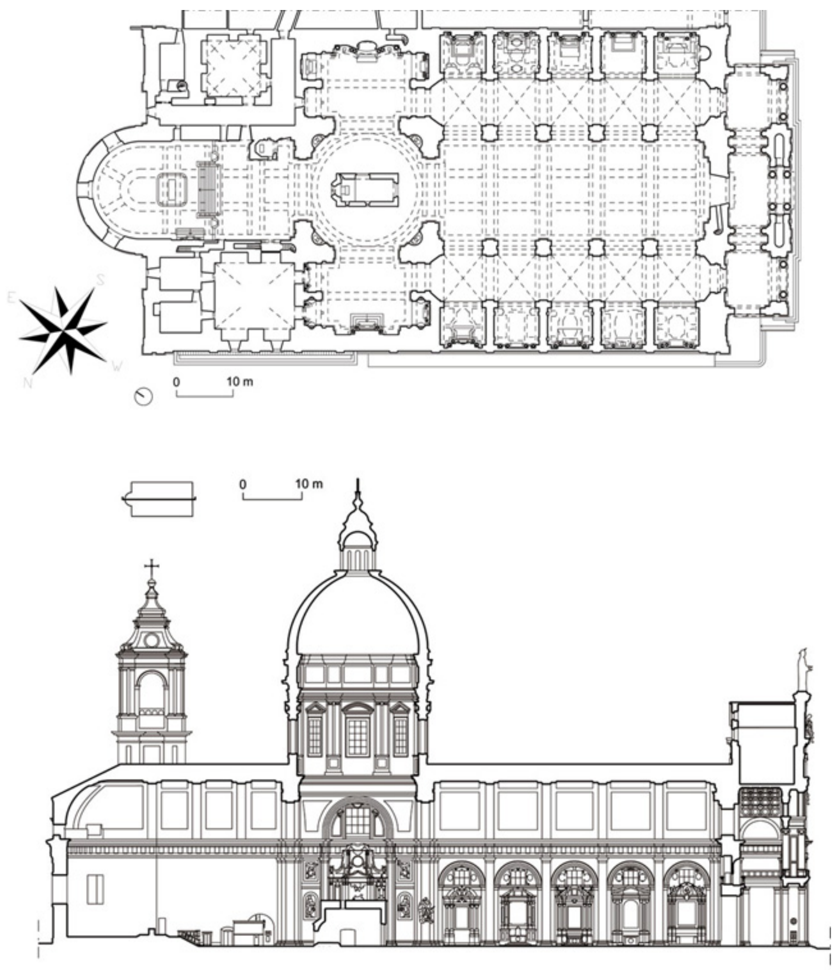
In order to preliminary assess the structural behavior of the dome, several dynamic experimental investigations have been carried out and ended with the installation of a simple vibration-based monitoring system, based on the use of a few high sensitivity accelerometers, placed at the top and the base of the drum, as well as temperature and humidity sensors. This paper presents and discusses the first results of the vibration-based monitoring of the drum-dome system, demonstrating the potential for using similar approaches for the preservation of this special kind of historic structures.

Figure 1: Basilica of Santa Maria degli Angeli in Assisi.

1 INTRODUCTION

Monitoring the structural integrity of historical constructions is an important topic for the conservation of the architectural heritage [1], that has received a considerable interest both from researchers and practitioners in the last decades [2, 3, 4, 5, 6, 7]. Within this context, vibration-based dynamic monitoring can be considered as a quite novel approach, if applied to cultural heritage. In particular, while the use of Operational Modal Analysis (OMA) techniques is well-established for performing dynamic structural investigations and/or implementing continuous monitoring of relatively new slender structures [8, 9], their application in the context of heritage monumental buildings is far less common. A few documented applications of vibration-based monitoring to monumental buildings are however available, whereby some literature studies have proposed the use of OMA techniques for the dynamic identification of masonry civil and bell towers [10, 11, 12]. On the contrary, applications to different kinds of historic structures are quite rare and only a few studies have proposed to use OMA techniques in the context of continuous dynamic monitoring systems [13, 14]. This is mainly due to the low levels of vibration typically exhibited by massive masonry buildings, as well as to their complex structural behavior, that makes the development of vibration-based continuous monitoring systems for cultural heritage preservation a new and worthwhile scientific and technical challenge.

In this paper, the results of ambient vibration tests carried out on a masonry dome, which lead to the installation of a permanent dynamic monitoring system, are presented. The case study considered here is the dome of the Basilica of Santa Maria degli Angeli in Assisi, recently added to Unesco's World Heritage List, which represents one of the most important focal points of the franciscan spirituality (Figure 1). Field measurements of the dynamic response of the structure have been carried out by installing high sensitivity accelerometers both at the top and at the base of the drum. Data are first processed to preliminary assess the structural behavior and to attain a proper configuration of the sensors layout for the monitoring system. The same



(a)

(b)

Figure 2: Basilica of Santa Maria degli Angeli in Assisi: (a) plan; (b) longitudinal section [15].

data are then continuously processed by using both classical Frequency Domain Decomposition (FDD) and Stochastic Subspace Identification (SSI) techniques. The results of the first months of monitoring are presented, providing an overall demonstration of the potential of this kind of measurements in the context of heritage preservation.

2 THE DOME OF THE BASILICA OF SANTA MARIA DEGLI ANGELI IN ASSISI

2.1 The architecture

The Basilica of Santa Maria degli Angeli in Assisi was built between the 16-th and the 17-th centuries, on the design of the architect Galeazzo Alessi. It consists of a latin cross plan, with 126 m and 65 m dimensions, with a nave, two aisles and a semicircular apse. The Basilica contains the Porziuncola, a little ancient chapel representing a symbol of Franciscan spirituality and an important pilgrims destination. This chapel is located at the intersection between the transept and nave. Figures 2(a) and 2(b) show the plan and the longitudinal section of the Basilica carried out after a recent architectural survey [15].

The presence of the Porziuncola inside the basilica, as well as the need to provide a visible sign for pilgrims coming from all over the world, have induced the architect to design an uncommonly high drum-dome system. In this way, the dome appears majestic and impressive owing to the singular slenderness and lightness of the drum. It is characterized by a single shell

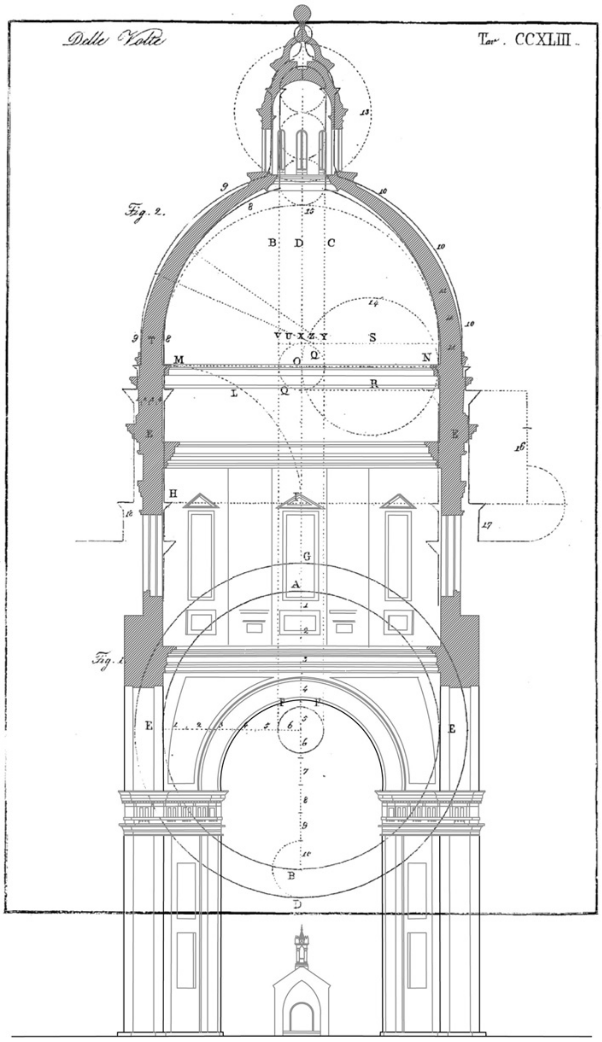


Figure 3: Superposition between Fontana's drawing and the dome section of the Basilica of Santa Maria degli Angeli [17].

and provided with an external staircase to climb up to the lantern. The inner diameter is of approximately 20 m and the variable thickness of the unique shell ranges from 1.80 m at the bottom, up to 0.90 m at the top. The inner perimeter of the drum is circular, while the outer one is octagonal; the coupled pilasters at the angles of the octagon become stiffening ribs over the dome's extrados, joining at the oculus, the base of the lantern, that gives to the architectural complex an overall height of approximately 75 m.

It should be noted that, if compared with the rules of construction illustrated in the most important architectural treatises, e.g. the work of Carlo Fontana [16], the drum appears to be very high. In particular, its height is more than twice the height that would correspond to the prescriptions proposed by Fontana, conferring to the structure a really unusual slenderness and unique architectural feature. This aspect is emphasized in Figure 3, where the section of the drum-dome system is superimposed to a drawing explaining the geometrical rules proposed by Fontana.

It is worth recalling that Fontana's graphical rules were developed for the design of some structural parts of the Vatican Temple, which made his treatise a fundamental reference for

Figure 4: Lineengraving of the basilica damage state after the 1832 earthquake. *Prospetto delle ruine del famoso Tempio di Santa Maria degli Angioli di Asisi*, by Cilleni Nepis.

architects of those times [19]. Nonetheless, the dome of the basilica of Santa Maria degli Angeli was a notable exception to those rules and differed from all other contemporary designs. This significant slenderness motivated the authors towards the implementation of a vibration-based monitoring system for the dome.

2.2 Evolution of the structural system

Throughout its history, the Basilica of Santa Maria degli Angeli was subjected to significant seismic events. The most important one was certainly the earthquake of 1832, which caused the collapse of the nave and of a portion of the left aisle (Figure 4). The drum-dome system was severely damaged, but did not collapse, conceivably because of its high flexibility and low natural periods of vibration. The strengthening of the drum with three orders of steel rings dates from this period. In the reconstruction phase, a particular attention was devoted to the cross section of the central vault and to the timber truss system of the roof designed by Poletti, in order to reduce the horizontal thrust acting on the lateral walls [20]. After the Umbria-Marche earthquake of 1997, the basilica was subjected to other phases of strengthening and restoration [21]. However, a pattern of cracks and micro-cracks, that can be attributed to seismic and static actions, is still evident both in the drum and the dome. The most significant through-wall cracks are located above the north-east side, for the presence of internal staircases and tunnels, and the west side of the drum.

3 ANALYSIS PROCEDURES AND MONITORING SYSTEM

3.1 Data processing

Field recorded vibration data have been processed using two different techniques. The first considered approach is the classic Frequency Domain Decomposition (FDD) based on the evaluation of the spectral matrix $\mathbf{G}(f)$ (i.e. the matrix of cross-spectral densities) of recorded accelerations, whose diagonal terms are the auto-spectral densities (ASD), while the out of diagonal are the cross-spectral densities (CSD). The time series are first resampled in order to estimate $\mathbf{G}(f)$ with a frequency resolution of 0.01 Hz. Subsequently, the contour plot of the first singu-

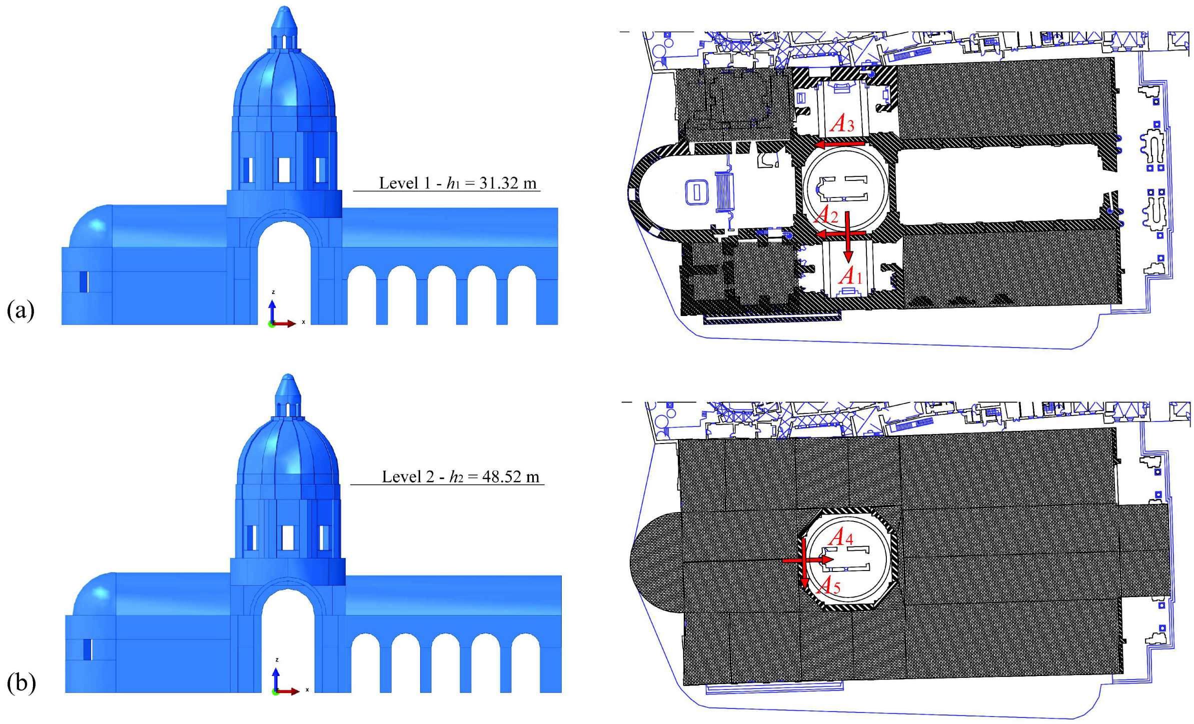


Figure 5: Structural monitoring system installed in the dome of the basilica.

lar value (SV) of the spectral matrix $\mathbf{G}(f)$ estimated in consecutive data sets has been obtained. This plot is commonly known as frequency spectrogram, which highlights resonant frequencies and their variation in time as local maxima of the SV contour plot and, consequently, of the energy content of the data, in the time-frequency domain.

The second considered approach is based on the Stochastic Subspace Identification (SSI) technique. This method has been used to identify the natural frequencies of the structure by a fully automated for step procedure [22, 23]: (i) run of SSI-data analysis, using the classic Canonical Variate Analysis (CVA) formulation, for different values of the order of the model and of the number of output block rows adopted to construct the block Hankel matrix of the data; (ii) elimination of noise modes on the basis of similarity checks between modal parameters estimates; (iii) clustering of remaining modes; (iv) extraction of mean values of modal parameters estimates with 95% confidence intervals, under variation of model's order and number of block rows of block Hankel matrix. Using the SSI technique to consecutive data sets it is possible to obtain a frequency time series of the lower structural natural modes.

3.2 Dynamic monitoring system

The monitoring system installed in the drum and the dome consists of five high-sensitivity (10V/g) uni-axial accelerometers placed at the base of the drum and at the base of the dome, as described in Figure 5. In particular, three accelerometers have been fixed on the easily accessible external side of the drum base (sensors A_1, A_2 and A_3 in Figures 6(a) and 6(b))). The sensors A_4 and A_5 have been placed in the only accessible part with highest location inside the dome shell (Figure 6(c)), at the top of the internal staircases which allow the access to the dome extrados. The data have been recorded by using a multi-channel system, carrier model cDAQ-9188 with NI 9234 data acquisition modules (24-bit resolution, 102 dB dynamic range and anti-aliasing filters), down-sampled at 100 Hz for storage purpose and stored in 30-minutes long

Figure 6: Images of the accelerometers installed at the base of the drum (a) and (b), and of the dome (c).

	ρ [t/m^3]	μ_E [MPa]	$\sigma_{ln,E}$	μ_G [MPa]	$\sigma_{ln,G}$
Brick	1.8	1500	0.2	500	0.2
Stone	2.2	2800	-	860	-

Table 1: Mechanical material properties: mass density (ρ); mean value (μ_E) and standard deviation of the logarithm ($\sigma_{ln,E}$) for the elastic modulus; mean value (μ_G) and standard deviation of the logarithm ($\sigma_{ln,G}$) for the shear modulus

time histories, representing the data sets. The monitoring system also includes humidity and temperature sensors, as well as displacement transducers monitoring the evolution of existing cracks. The related information is however not illustrated in this work and, therefore, these additional sensors are not considered.

4 ANALYSIS OF RESULTS

4.1 Preliminary numerical model

The Basilica of Santa Maria degli Angeli has been investigated focusing on both historical and structural aspects [17, 18]. As far as the structural analysis is concerned, a preliminary Finite Element numerical model has been developed in order to investigate the static and dynamic behavior of the structure, with a focus on the drum-dome system. The model details the central core of the basilica, i.e. the triumphal arches, the drum and the dome, while the remaining parts of the basilica are considered as lateral restraints. In this way, it has been sufficient to include a rough model of the nave, the transepts and the apse to reproduce a consistent lateral stiffness.

A peculiarity of the developed numerical model is the probabilistic approach for the estimation of the eigenfrequencies and eigenmodes starting from a stochastic model for the elastic moduli of the materials. The main constituent material is brickwork everywhere, except for the stone pillars of the nave. An homogeneous material with orthotropic elastic behaviour has been considered, in which the values of stiffness have been selected from the recent instructions proposed by the Italian National Research Council [24], with their lognormal distribution parameters (Table 1).

A set of 1000 samples have been generated for both the Young's modulus (E) and shear modulus (G) of the brickwork (Figure 7), and then multiplied by a coefficient $\alpha = 1.5$ which takes into account the good condition of the mortar.

Figure 8 shows the eigenproblem solutions of the first modes. For each mode the distribution of the corresponding frequencies for the 1000 samples of the elastic parameters is reported. It should be noted that all considered modes are flexural in x and y directions, with the only

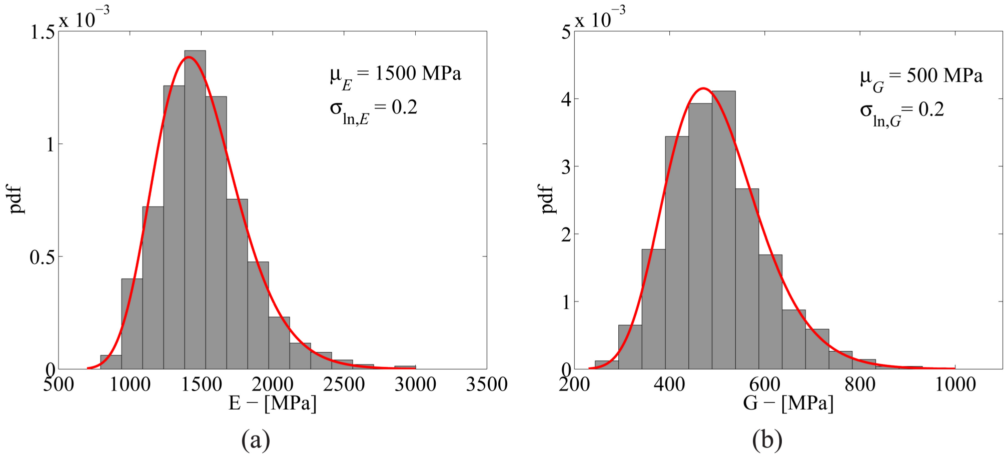


Figure 7: Generated values of Young's modulus (a) and shear modulus (b) from the statistical moments of the related distributions.

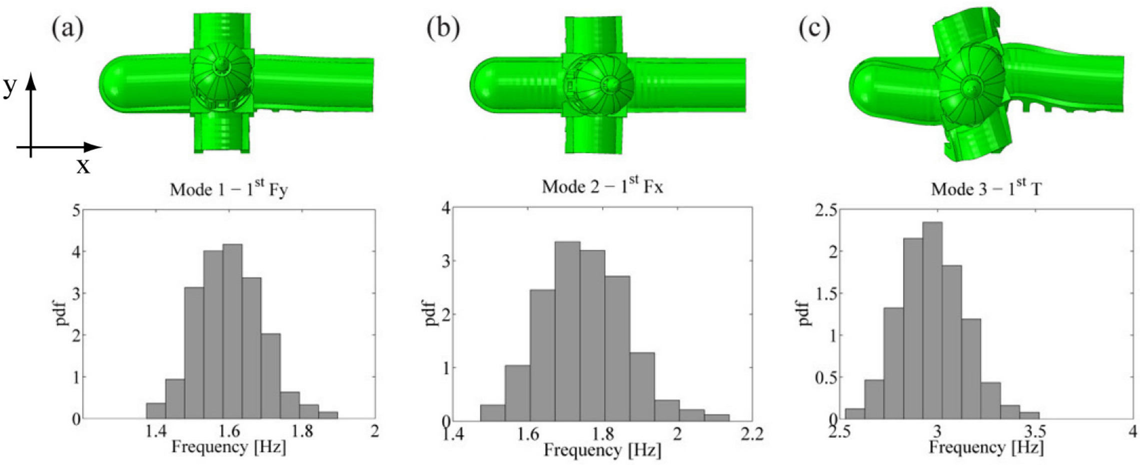


Figure 8: Modal shape and distribution of the related frequencies of the first seven modes derived by FE model by varying material stiffness [25].

exception of the third mode, which is a torsional mode. The x and y directions are defined according to the reference system of the numerical model (Figure 8).

4.2 Dynamic identification of the modal parameters and frequency tracking

The dynamic monitoring system has been started on October 16-th 2015. Figure 9 shows an example of acceleration time histories of a sample 30-minute data set, with excitation mainly given by micro-tremors due to road traffic around the Basilica and by wind loading. The very low levels of vibration in operational conditions are especially noteworthy, whereby peak accelerations are of the order of 0.2-0.3 mm/s^2. The different levels of noise in the signals can be conceivably due to the length of the cables connecting the sensors to the data acquisition unit.

The modal parameters of the structure have been estimated by means of the aforementioned SSI technique. In particular, the analysis has allowed to clearly identify the first five natural modes, where the first two modes are flexural in the y (Fy1) and x (Fx1) directions, respectively, the third mode is torsional (T1), and the last two modes are, again, flexural in the y (Fy2) and x (Fx2) directions, respectively. Figure 10 and Table 2 summarize the results of the modal parameters with their mean values and standard deviations identified from October 16th 2015

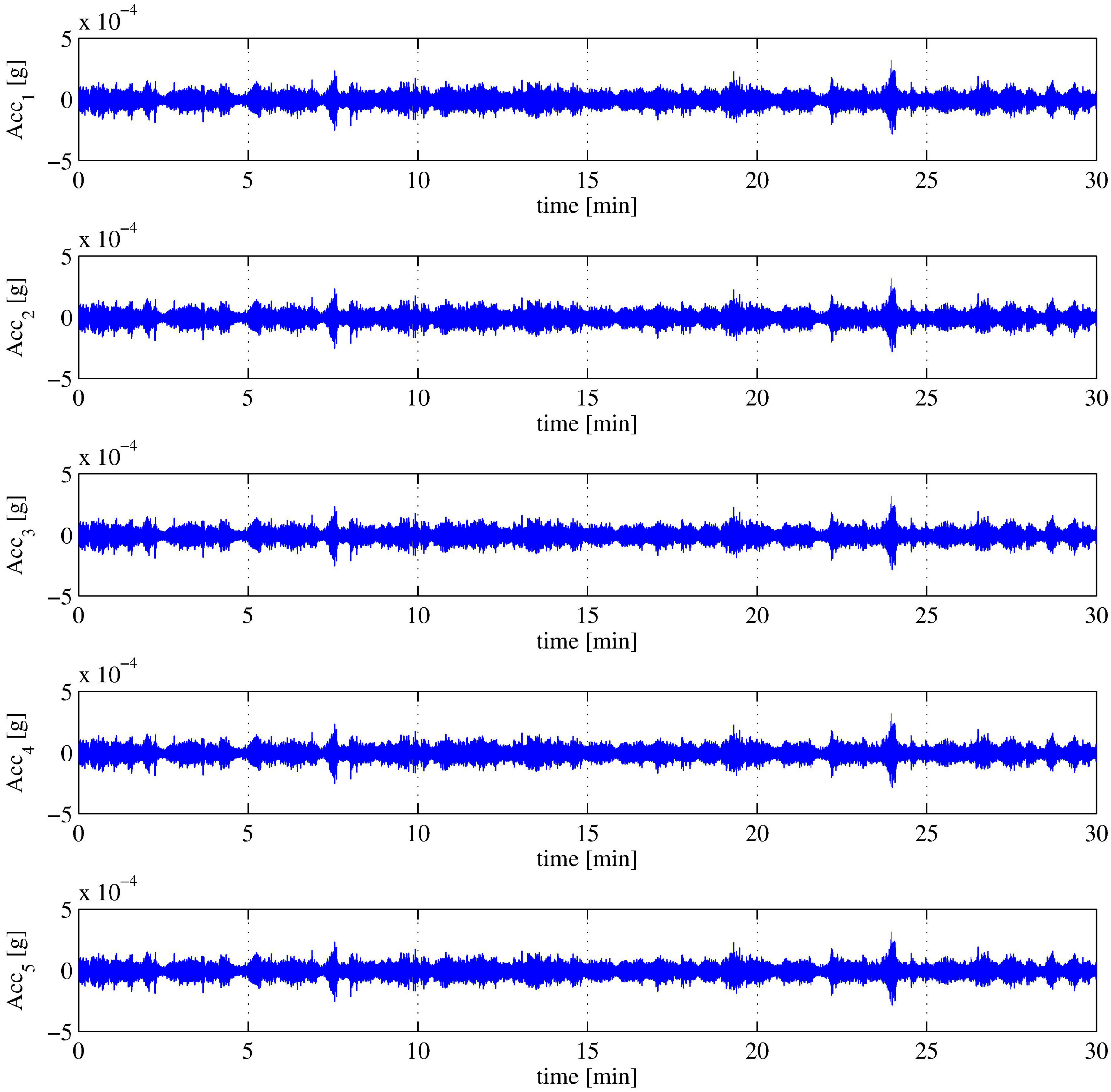


Figure 9: Sample of a 30-minutes recorded data.

Mode	Type	Frequency [Hz]	
		μ_f	σ_f
1	Fy1	1.77	9.25e-3
2	Fx1	1.81	1.10e-2
3	T1	3.08	1.01e-1
4	Fy2	3.51	4.78e-2
5	Fx2	4.40	5.57e-2

Table 2: Identified modal frequencies of the drum-dome system: mean values μ_f and standard deviations σ_f.

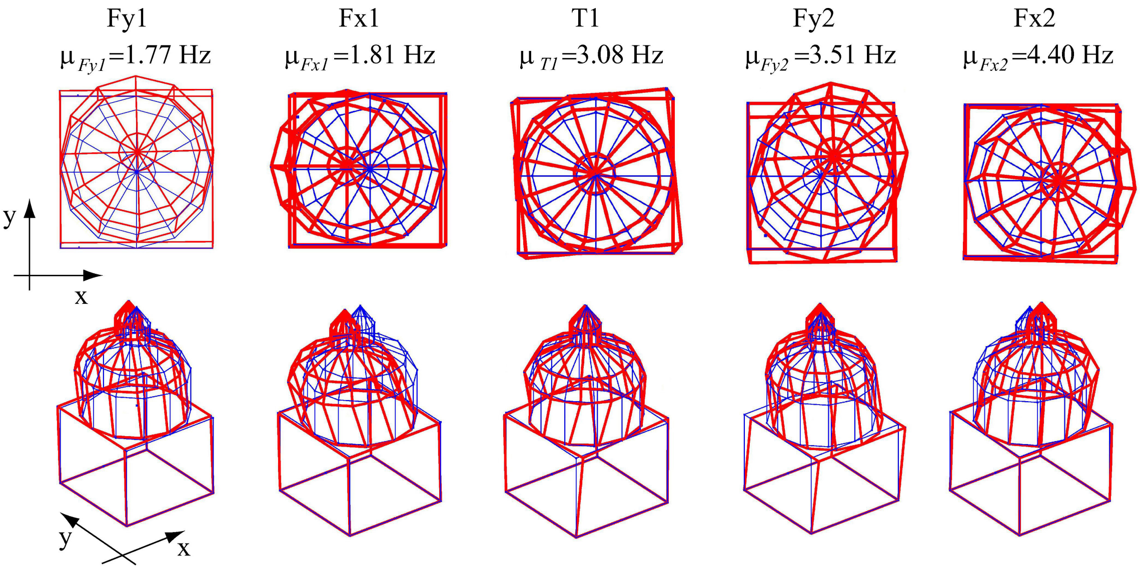


Figure 10: Representation of the identified modal shapes.

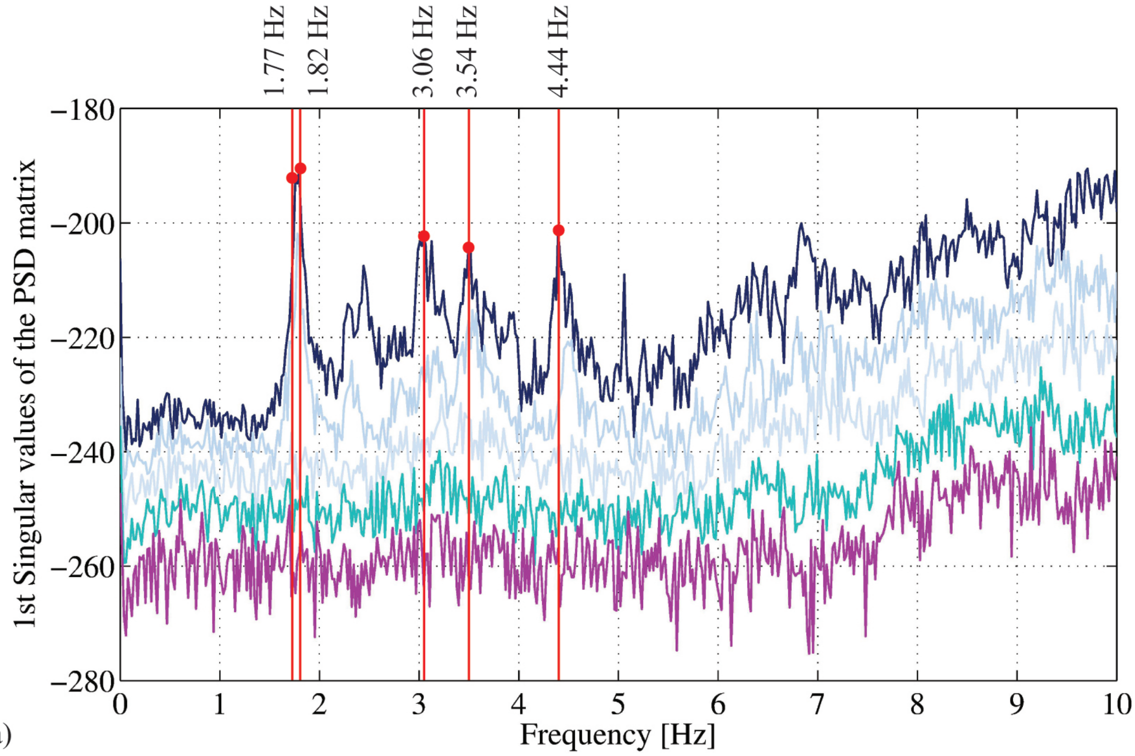
to January 4th 2016.

The application of the FDD technique has allowed to extract the first resonant frequencies through the peak-peking method. As an illustrative example, Figure 11(a) is a plot of the singular values of the power spectral density matrix of recorded accelerations as a function of frequency, for the sample data set in Figure 9. The first five resonant frequencies identified by SSI analysis can be clearly detected in the plot of Figure 11(a). Peaks associated to higher frequencies are also visible in this plot, which might conceivably correspond to higher order modes. A final decision about the nature of these peaks goes however beyond the purposes of the present investigation.

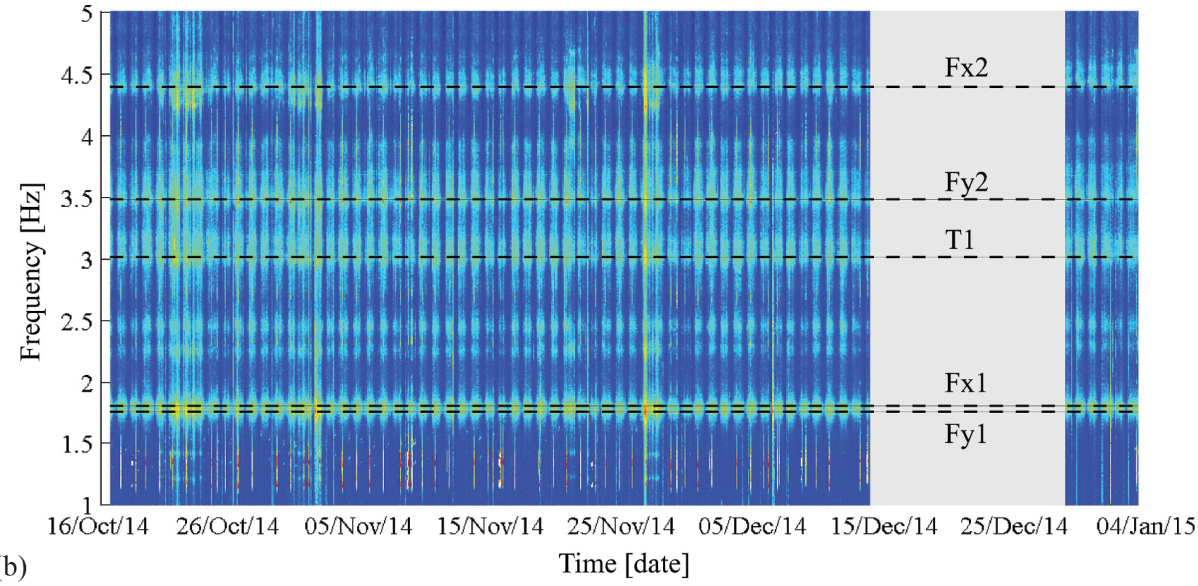
Figure 11(b) shows the spectrogram of the first singular value of the PSD matrix of the five acceleration records over the monitoring period. The traces of the first five modal frequencies are clearly visible in this plot and are indicated through dashed lines. By a closer inspection of the analysis results, it could be verified that these modes corresponds to those identified by FDD in a single data set, as discussed above. Another remark on the plot of figure Figure 11(b), is the presence of daily vertical lines that are associated with an increase in vibration energy during day-time and a decrease during night-time. This periodicity is conceivably associated to the periodicity of traffic intensity around the basilica.

Figure 12 shows the identified natural frequencies versus time, as obtained by the application of the aforementioned fully automated SSI technique on the data sets recorded over the monitoring period. The presented results are in perfect agreement with those obtained by spectral analysis of accelerations, as presented above. In particular, a quite clear tracking of the frequencies of the first five modes is achieved. Daily and long-term fluctuations of such frequencies are also clearly visible in this plot and conceivably attributable to changing environmental conditions, primarily ambient temperature. Also, natural frequencies are almost systematically identified during the day-time, while some frequencies are missing during night-time, due to a comparatively lower level of excitation.

From the results presented above, some comments on the agreement between experimentally identified and numerically predicted natural frequencies are mandatory. This comparison reveals that the frequencies of the second and the third numerical modes are in a good agreement



(a)



(b)

Figure 11: (a) Singular values of the power spectral density matrix and identification of the first resonant frequencies. (b) Spectrogram of the natural frequencies obtained by the FDD technique.

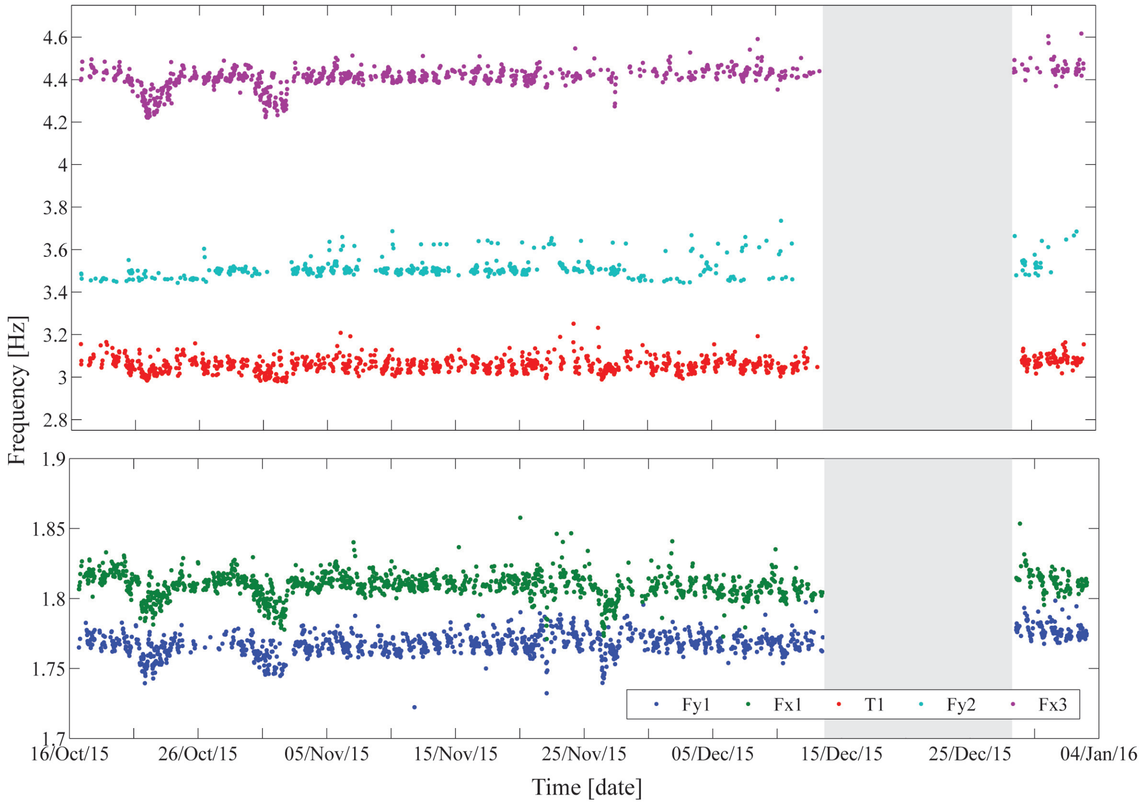


Figure 12: Frequency tracking of drum-dome system obtained by SSI technique.

with experimental results. The comparison with the higher modes requires further investigations which have not been carried out in this work. A final remark concerns some resonant frequencies in the range around $2.3 \div 2.5$ Hz which are often observed (e.g. Figure 11(a)). These phenomena are probably to be ascribed to the lateral restraint effect of the surrounding basilica. The numerical model is not able to describe these effects since, at this preliminary stage, the lateral structural elements are not fully reproduced. However, it can be concluded that the agreement between the preliminary developed finite element model and the identified natural frequencies is acceptable.

5 CONCLUSIONS

In this paper the first results obtained by a vibration-based monitoring system installed in the dome of the Basilica of Santa Maria degli Angeli in Assisi have been presented. The structural modal parameters and, in particular, the natural frequencies of the lower order modes, have been estimated over time in a continuous fashion using classic spectral analysis and a more advanced automated SSI technique. These natural frequencies have been also compared with those obtained by a FEM model developed in a previous study. In general, a good agreement between numerically predicted and experimentally identified modal parameters has been observed, both for natural frequencies and mode shapes.

Overall, the results presented in the paper represent a first attempt to monitor the behavior of large domes using vibration measurements and automated operational modal analysis. The presented results are promising towards the implementation of a vibration-based SHM procedure aimed at the early detection of damages in the structure caused by low return period earthquakes or other types of dynamic loads.

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