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LONG-TERM MONITORING OF A MASONRY TOWER WITH WIRELESS ACCELEROMETERS

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Abstract

During the last decades, significant efforts have been made to define appropriate Structural Health Monitoring (SHM) frameworks based on the vibration signatures collected by accelerometers. Data-driven approaches are increasingly adopted for damage detection through the identification of anomalies in the distribution of the frequencies. This paper analyzes the long-term monitoring data acquired from a system installed on the Matilde tower in Livorno (Italy). The tower is a historic masonry structure monitored since the end of 2018 using a wireless sensor network developed during the MOSCARDO project.

Keywords: structural health monitoring, data-driven methods, damage detection, natural frequencies, environmental parameters, automated operational modal analysis.

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1 INTRODUCTION

Structural Health Monitoring (SHM) has become widely applied to large civil structures. Among all the structures, cultural heritage buildings are particularly challenging ([1], [2], [3]). The sensors that measure the damage-sensitive features should be less invasive to limit the visual impact and preserve the original features. Thus, small wireless sensors should be preferred to the cabled ones and a limited number of spots should be selected. As a result, the sensor layout is sparse, and the measuring sensors have a low resolution and/or a low Signal-to-Noise Ratio. In this scenario, appropriate procedures aimed at minimizing bias should be developed. The Continuous SHM approach can be applied, furnishing a huge dataset that must be processed and deeply analyzed. The resonant frequencies extracted with Automated Operational Modal Analysis procedures are commonly selected as damage-sensitive features ([4], [5], [6], [7], [8]). However, these quantities can be more sensitive to the environmental parameters than to the damage.

This paper presents the outcomes of the monitoring campaign conducted on a masonry tower selected as test case within the framework of the MOSCARDO project (carried out by Infomobility S.r.l., Engineering Italy Solutions S.r.l., ISTI-CNR and the University of Florence from April 2016 to October 2018 and funded by the Region of Tuscany and the Italian Ministry of Education, University and Research), aimed at developing a system for the structural health monitoring of ancient constructions ([9], [10], [11]).

The MOSCARDO monitoring system is composed by Wireless Sensor Networks (WSNs) for the acquisition of structural (accelerations at prescribed points of the structure) and environmental data (pressure, humidity, and temperature), coupled with a flexible and reliable Internet of Things communication infrastructure. A further essential component of the system is the so-called Monitoring Control Center (MCC), a cloud-based platform to provide services for storage, processing, and interpretation of data coming from the WSNs.

The MCC architecture collects and stores large amounts of data to monitor the structure in time and provide continuous supervision. The Matilde tower in Livorno (Italy) has been monitored for five years, since the end of 2018, with some interruptions due to Covid-19 pandemic. The paper describes the dynamic monitoring system and the results obtained, focusing on the correlation of the modal properties with the environmental parameters.

2 THE MATILDE TOWER

The Matilde tower is an iconic building in the harbor of Livorno. Characterized by massive dimensions (about 12 m of external diameter and 30 m height), it was a crucial defensive structure against the Saracen pirates' raids in the medieval era. Nowadays, the tower is part of a complex fortress "Old Fortress") that was built around the tower.

XIII century   XVI century   XX century

Figure 1: The evolution of the buildings around the tower over the centuries.

The structure underwent several modifications over the centuries, as showed in Figure 1. In the XIII century, the tower was part of a minor, squared fortification under the control of the

Pisa Republic. Then, under the Medici's domain, the defensive structure was further enhanced to a larger fortress with three bastions ("Ampolletta", "Canaviglia" and "Capitana") and two main gates by Antonio da Sangallo the Elder and Antonio da Sangallo the Younger. Lately, the structure was converted into a palace by Cosimo I de' Medici, and in the XX century, the fort became a prison. During the WWII, the complex sustained extensive damage, and most of the buildings were destroyed apart from the Matilde tower.

To date, the fortress is in front of the old dock of the port of Livorno (Figure 2), which is still used by the ferry boats departing to the Sardinia and Corsica islands. As a test case of the MOSCARDO project, the tower was equipped with seven MEMS wireless accelerometric sensors since October 2018. The challenges were represented by using cheap sensors with a low visual impact in a location subjected to harsh environmental conditions and several external noises due to the port activities.

Figure 2: The Matilde tower and the Old Fortress.

3 THE STRUCTURAL HEALTH MONITORING SYSTEM

To design the long-term monitoring sensors layout, preliminary dynamic tests were carried out in the first months of the MOSCARDO project by using 12 high sensitivity piezoelectric accelerometers (PCB 393-C with a range of 2.5 g, sensitivity of 1 V/g and PCB 393-B31 with a range of 0.5 g, sensitivity of 10 V/g), in order to assess the dynamic behavior of the tower.

These tests were performed using a refined grid of sensors in order to accurately identify the dynamic behavior of the Matilde tower and to design the sensor setup of the long-term monitoring system. The prior knowledge of the dynamic behavior is in fact a basic datum for the design of a suitable long-term monitoring system, especially for cultural heritage buildings.

The long-term sensors layout adopted is showed in Figure 3. This layout is made up by two mono-axial and one biaxial accelerometer placed at level 2, one mono-axial and one biaxial accelerometer placed at level 0, for a total of seven accelerometers equipped with Safran Colibrys SA transducers. Optimization of sensor layout was performed to assure energy efficiency of the network. Data were collected by recording fifteen minutes every hour with a sampling frequency of 50 Hz. This acquisition period is greater than 2000 times T_1, where $T_1 = 0.378$ s is the fundamental period of the tower.

The environmental conditions were monitored with two meteorological stations: one inside and one outside the tower, measuring temperature and humidity. An anemometer measuring the average wind speed and direction was installed at the top of the last level.

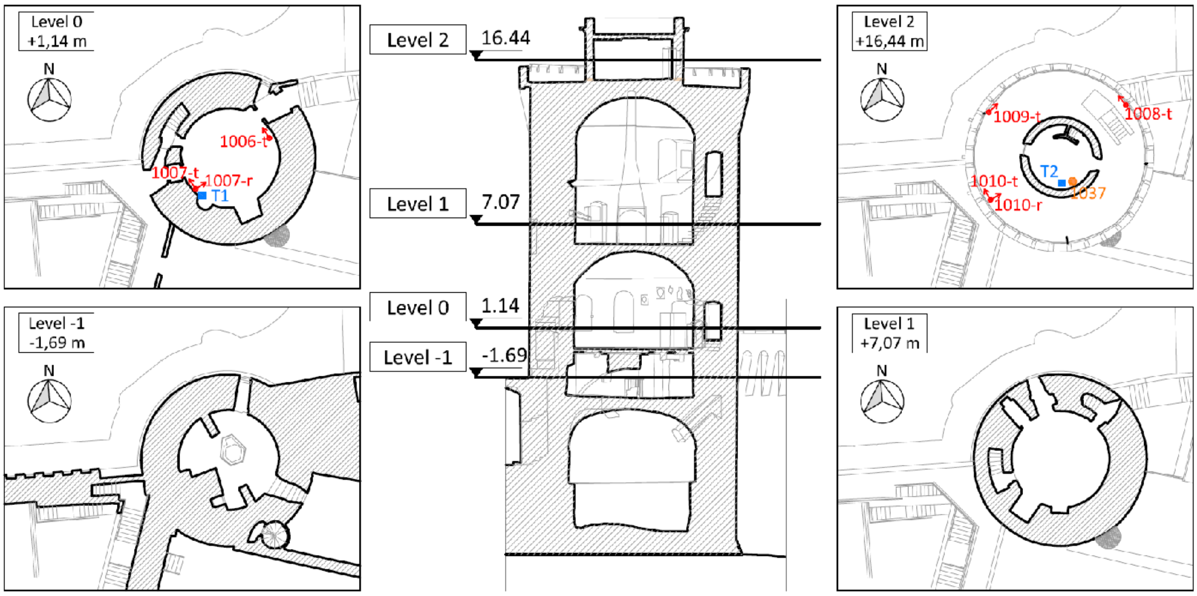


Figure 3: Layout of the sensors installed on the Matilde tower.

4 FIVE YEARS OF MONITORING

The long-term monitoring system has been working since late 2018 to date with hourly acquisitions. Unfortunately, the long-term monitoring system has been out of order for about two years, with additional interruptions due to the COVID-19 pandemic (grey-shaded areas in the following figures).

Hence, the data were collected from October 2018 to April 2020, then from April to May 2021 and, eventually, from March 2022 up to now. At least about 22,000 acquisitions are anyway now available, and some preliminary observations about the tower dynamics can be drawn.

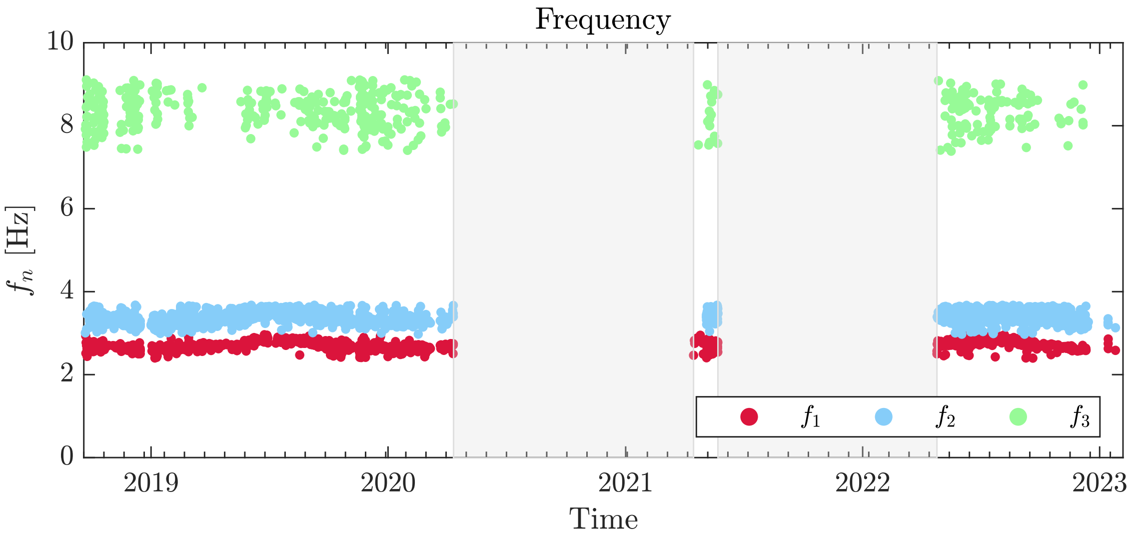
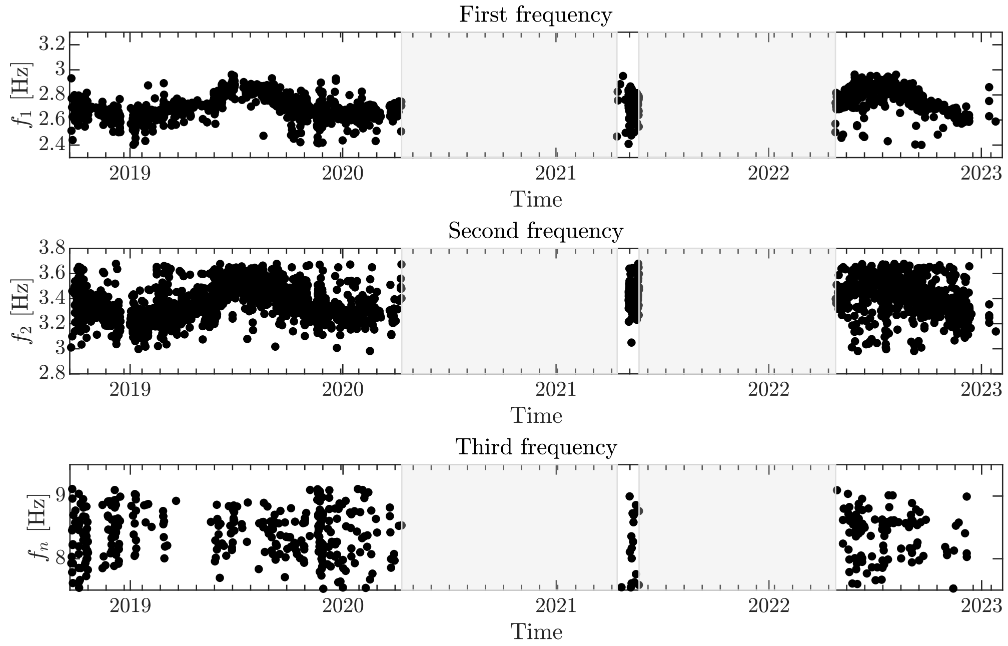


Figure 4: Frequencies identified in the tower (the grey-shaded areas represent the system out of service).

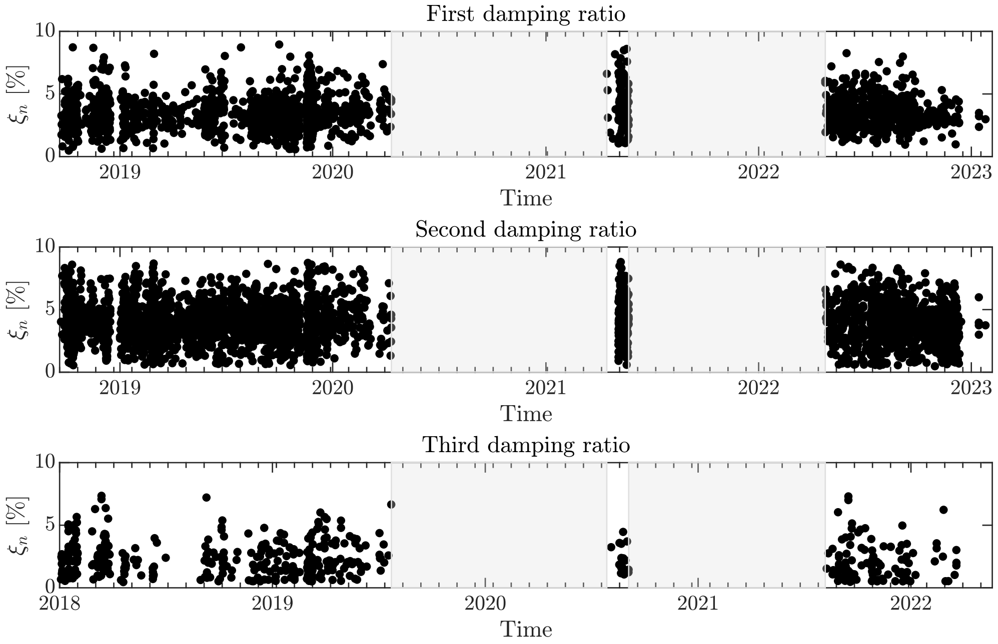

First frequency

Second frequency

Third frequency

Figure 5: Zoom of the first three frequencies identified in the tower
(the grey-shaded areas represent the system out of service).

After the dataset processing, the modal properties (resonant frequencies, damping ratios and mode shapes) were extracted and tracked via the A-OMA procedure described in [12], and then the frequencies were tracked over time with an adaptive procedure as described in [13].


First damping ratio

Second damping ratio

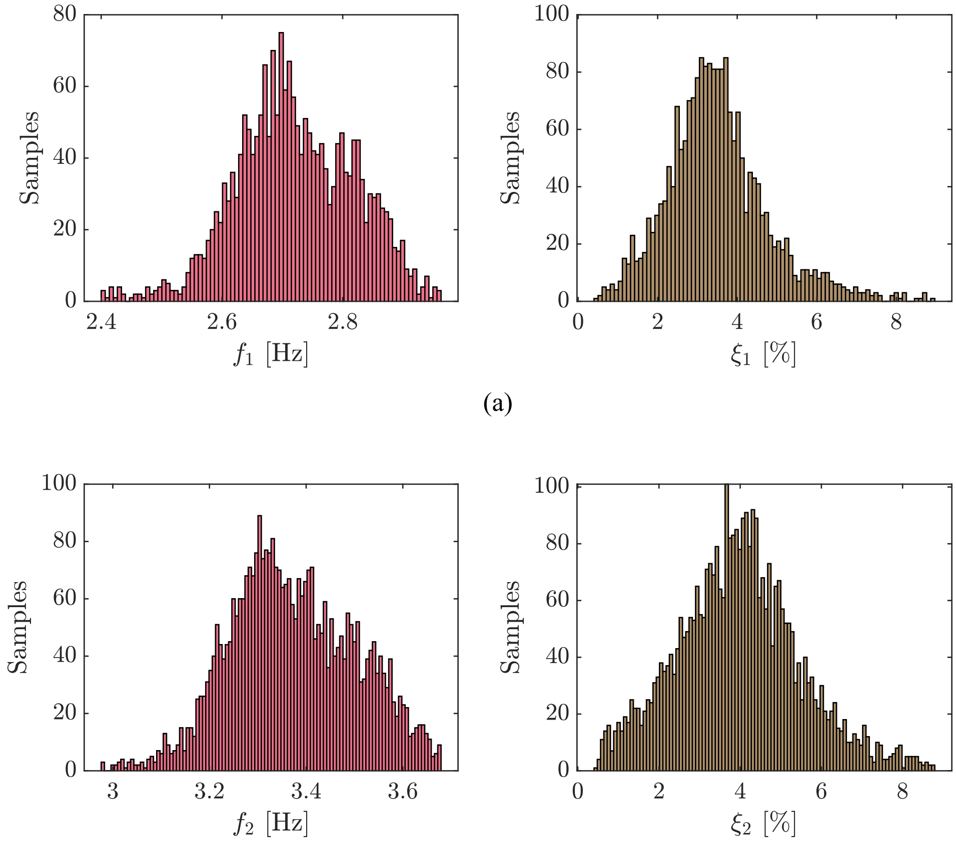
Third damping ratio

Figure 6: Zoom of the first three damping ratio identified in the tower
(the grey-shaded areas represent the system out of service).

At least three frequencies can be identified, as shown in Figure 4. It is clear how the first two modes are well represented with a high population, while the third mode is more variable and with a limited number of extracted data. From the zoom shown in Figure 5 and Figure 6 a clear seasonal trend can be detected for the first two frequencies; the third frequency, like the damping ratios, seems to be uncorrelated with the seasonal effects due to the environmental conditions. Table 1 reports the statistical moments of the tracked modal parameters, setting a maximum difference in terms of frequency equal to the 10% (i.e. $\Delta f/f$) and a degree of correlation in terms of modal assurance criterion equal to 0.8. While the resonant frequencies are characterized by a smaller variance and a distribution that can be assumed as Gaussian, the damping ratios exhibit higher variability. The statistical distribution of the frequencies and damping ratios is showed in Figure 7.

Modal parameter	**Samples**	**Mean**	**Variance**	**Skewness**	**Kurtosis**
$\mathbf{f_1}$	2071	2.721	0.009	-0.129	2.918
$\boldsymbol{\xi_1}$	2071	3.505	1.623	0.773	4.372
$\mathbf{f_2}$	3526	3.373	0.017	0.063	2.572
$\boldsymbol{\xi_2}$	3526	3.964	2.298	0.269	3.113

Table 1: Statistical moments of the tracked modal parameters.



(a)

(b)

Figure 7: Statistical distribution of frequencies and damping ratios: (a) first mode and (b) second mode.

5 CORRELATION WITH THE ENVIRONMENTAL CONDITIONS

The environmental parameters were collected by two meteorological stations installed respectively inside and outside the tower. Despite the missing data, the data recorded and reported in Figure 8 are useful to characterize the variability of the dynamic properties extracted from the dataset gathered by the long-term monitoring system.

The temperatures collected inside and outside exhibit a good number of samples (respectively equal to 22285 and 11102), with a variability that ranges from 2.34 to 36.18 °C and 1.41 to 32.97 °C. Unfortunately, the sensors outside and inside did not always work simultaneously, thus the thermal gradient can be calculated only in 6503 samples as shown in Figure 9.

The humidity measured in the outdoor and indoor stations are the same for a consistent number of samples, even if the measures in the last part of the 2022 seem to be corrupted. The average wind speed recorded over 20 minutes, was clustered in 12331 samples. It reached the maximum value of 23.4 m/s on the 26 of February 2020, corresponding to a strong gale state in the Beaufort scale.

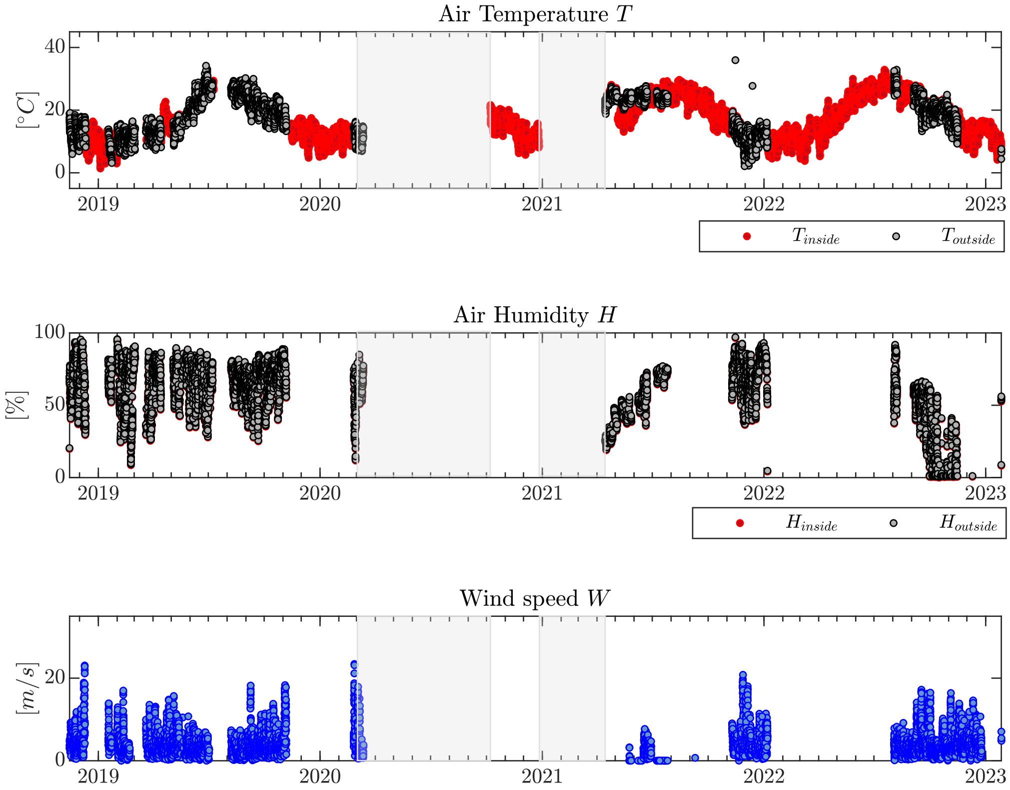


Figure 8: Environmental parameters collected by the long-term monitoring system.

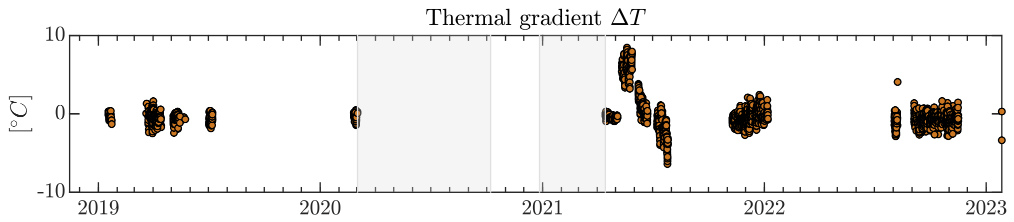
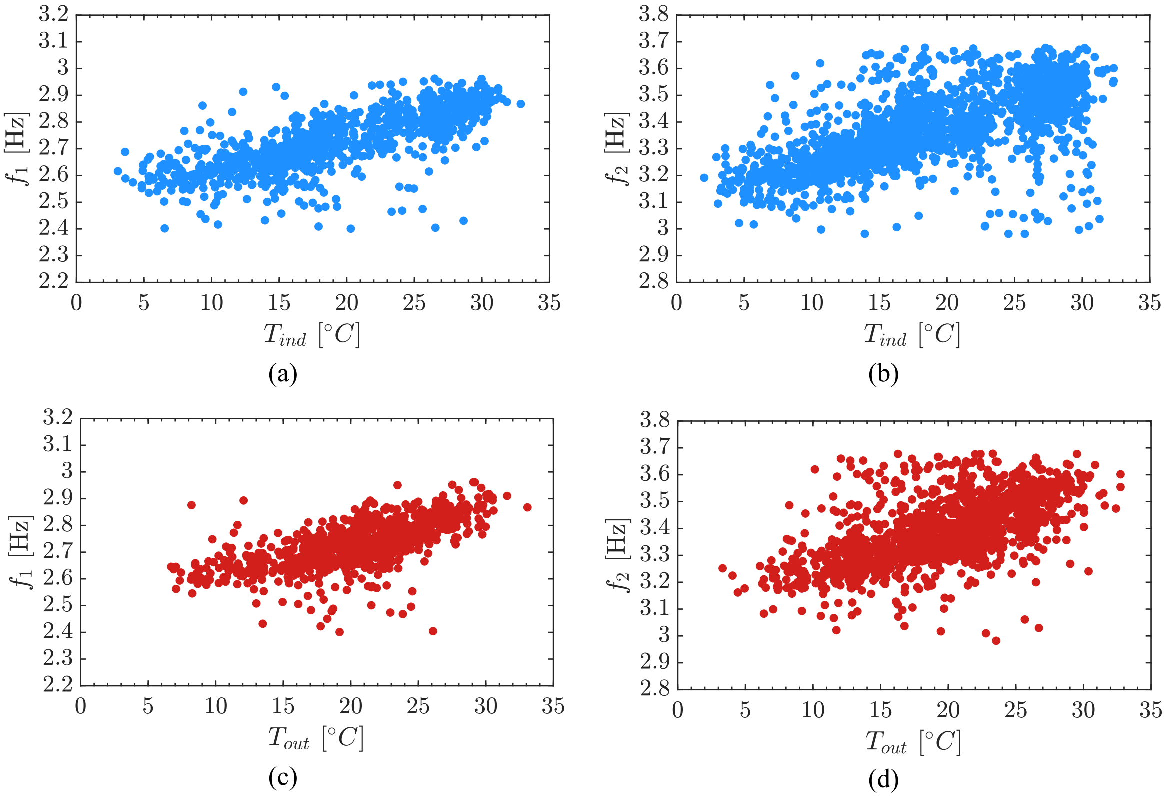


Figure 9: Thermal gradient on the tower calculated as the difference between the temperature measured outside and inside.

Considering that the structure is not heated during the winter nor cooled during the summer, the variations in terms of temperature depend only on solar radiation. As reported in Figure 8, a not significant difference was measured during the available time windows. Thus, the correlations between the frequency and the temperature measured inside and outside are very similar, with difference related mainly to the number of samples available in both cases. Moreover, a positive correlation can be observed in both cases, indicating a “stiffening” effect of the masonry when the temperature increases. This fact was already observed in the previous studies ([14], [15]) and it has been attributed to the expansion of the masonry blocks with a consequent closing of the cracks along the mortar joints. It is wort noting that the variation in terms of frequency ranges between the 15 and 20% for the first two modes, implying a high effect of the environmental conditions on the two main frequencies.



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

Figure 10: Frequency correlation with the temperature recorded indoor for the first (a) and second (b) resonant frequency respectively and the outdoor temperature [(c) and (d)].

6 CONCLUSIONS

This paper describes the application of the MOSCARDO system to the Matilde tower in Livorno. This case study allows assessing the performance of the system in long-term, continuous monitoring of heritage structures. From the data available it was possible to clearly identified the first two modes, highlighting a consistent variation of the resonant frequencies due to the seasonal variations of the temperature. A positive correlation was found for both the resonant frequencies with the temperature with an interval of variation of about 15-20%. Then, as well known, the resonant frequencies can be selected as damage-sensitive features for SHM purposes only cleaning the data from the environmental effects. Moreover, the system cannot clearly identify the higher modes that usually are mainly affected by variations in case of a structural damage. The case study described in the paper constituted a valuable test bed for assessing the capabilities and reliability of the MOSCARDO system. The monitoring campaign and the analysis of the recorded data paved the way for future technological enhancements of the system and the development of advanced numerical tools.

ACKNOWLEDGEMENTS.

The monitoring and control centre (MCC) and the wireless sensor network constituting the MOSCARDO system have been developed within the framework of the MOSCARDO project. MCC has been developed and deployed by Infomobility (www.infomobility-italia.com); sensor nodes hardware and related firmware have been designed and made by EIS (www.eis-italia.it). Part of the research activity related to the analysis is funded by Infomobility S.r.l., ISTI-CNR and the Region of Tuscany through the STRENGTH project 2022-2024.

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