One-Year Dynamic Monitoring the Main Spire of the Milan Cathedral

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Abstract. One of the most remarkable structural elements characterizing the Milan Cathedral is its main spire, reaching the height of about 108 m and supporting the statue of the Virgin Mary. The Main Spire, built in Candoglia marble and completed in 1762, is about 40 m high and stands on the *tiburio* of the cathedral (i.e., the prismatic structure with octagonal base built around the main dome). The spire consists of a central column which is connected through a spiral staircase to 8 perimeter columns, with each column being stiffened by a flying buttress. The structural arrangement is completed by (i) metallic clamps and dowels, connecting the marble blocks, and (ii) metallic rods, connecting the perimeter columns to the central core.

A large monitoring system has been recently designed and installed in the Milan Cathedral, aimed at enhancing the knowledge and assisting the condition-based structural maintenance of the historic building. The new monitoring system includes temperature sensors and seismometers (electro-dynamic velocity sensors) at 3 levels of the Main Spire as well as a weather station at the top of the same spire.

After a concise historic background on the Main Spire of the Milan Cathedral and the description of the sensing devices installed in this sub-structure, the paper focuses on the dynamic characteristics of the spire and their evolution during the first year of monitoring.

Keywords: Automated modal identification · Cultural heritage structures · Dynamic monitoring · Environmental effects · Natural frequencies

1 Introduction

The Milan Cathedral (Fig. 1a) is a monumental cross-shaped church partly designed in Gothic style, whose structural construction took more than 4 centuries, since the beginning of apse erection in 1386 until the façade finalization in 1813 [1]. The Main Spire (Fig. 1b, c), erected between 1765 and 1769, is one of the most iconic features of the cathedral [1, 2].

The preservation and maintenance of the many the structural integrity of the cathedral are currently hindered by the dimensions and the complexity of the building, as well as by the difficulty to reach and inspect several structural elements. A Structural Health Monitoring (SHM) project [3] has thus been devised, with the three-fold objective of assisting the structural inspections, early detecting the onset of anomalous

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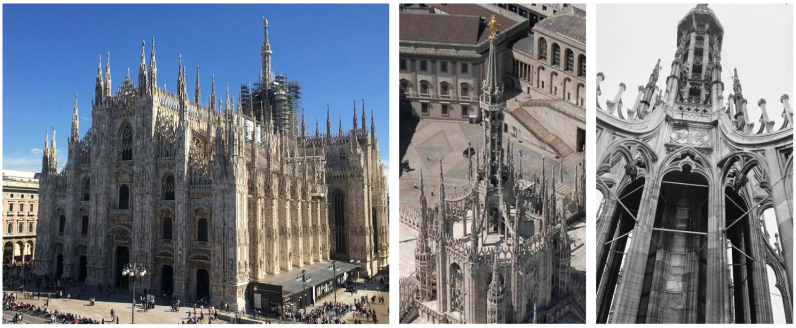
behaviour, and improving the knowledge of the building through the collection of a large archive of experimental data.

The monitoring system of the Milan Cathedral has been designed with specific attention to the Main Spire, which already underwent several restoration works [1, 2], despite its relatively recent construction. A quite spread monitoring system has been installed on the Spire, aimed at monitoring both the dynamic properties of the spire and its quasi-static deflections, along with the environmental conditions.

The effective application of vibration-based investigations of slender historical structures [4] has motivated the installation of a dynamic monitoring system in the Main Spire: the modal parameters are extracted from the collected time series, providing useful information on the global structural performance.

Recent studies have revealed that a statistical analysis of the collected natural frequencies can successfully identify the occurrence of structural anomalies (see e.g. [5, 6]). The same studies also address the environmental influence over the natural frequencies, which should be removed to enhance the novelty detection. The methodology adopted to exploit the dynamic signatures of the Main Spire for SHM purposes and the results of the first year of the dynamic monitoring are addressed in this study.



(a) (b) (c)

Fig. 1. View of the (a) Milan Cathedral and (b) its Main Spire; (c) metallic rods connecting flying arches of the Main Spire (courtesy of *Veneranda Fabbrica del Duomo di Milano*).

The paper is subdivided as follows. A concise description of the Main Spire and its dynamic monitoring system is given in Sect. 2. The dynamic properties of the spire are described in Sect. 3, whereas the evolution in time of natural frequencies and the peculiar influence of environmental conditions are discussed in Sect. 4.

2 The Main Spire and the Monitoring System

2.1 Description of the Main Spire

The Main Spire of the Milan Cathedral, Fig. 1b–c, is a 45 m long vertical cantilever, resting on the main dome at 65 m from the ground. The typical cross-section of the spire is a hollow cylindrical pier surrounded by eight slender columns. The connections among the perimeter columns are provided by ornamental elements, whereas the main pier and the perimeter columns are connected by spiral staircase, that allows reaching the Upper Belvedere, rising at 91.7 m from the ground. Eight inverse flying arches (Fig. 1c) provide lateral stiffening to the spire, conveying the lateral thrust to the vertical load-bearing walls of the Tiburio. The spire is finally crested with a pinnacle 14.8 m high, on top of which is lodged the statue of the Virgin Mary (Fig. 1).

The Main Spire differs from the spires of other Gothic Cathedral due late construction of the spire (between 1769–1774), both from an architectonic and a structural viewpoint. In particular, the spire was originally designed as a combination of metallic elements, Candoglia marble blocks and masonry. The presence of metallic reinforcement plays a key role in stiffening the spire, given the presence of (a) minor clamps connecting the adjacent marble blocks, (b) metallic rods connecting the eight perimeter columns and the inner pier (Fig. 1c), and (c) flat-rolled profiles running across the overall height of the central column.

2.2 Description of the Monitoring System

The monitoring system installed in the Main Spire comprises SARA SS45 seismometers (electro-dynamic velocity transducers (Fig. 2c), a class of sensors that has been recently employed in dynamic monitoring of historical structures (e.g. [3, 8]), due to several benefits, including:

a) high sensitivity (78 V/[m/s]) and the excellent performance of electro-dynamic transducers in the low frequency range ($f \leq 100$ Hz), fully suitable for the application in vibration testing or monitoring of civil engineering and cultural heritage structures;
b) the possibility of estimating the displacement time series by integrating the velocity records, so that data directly related to the stiffness (and especially useful for the slender Main Spire) are conceivably available;
c) the reduced cost of the sensors, when compared to state-of-the-art high sensitivity accelerometers of comparable technical characteristics.

The instrumental setup comprises 9 seismometers installed at 3 levels of the Main Spire, as exemplified in Fig. 2:

(a) 1 tri-axial seismometer at the base of the spire (+65.9 m);
(b) 3 horizontal uni-axial seismometers at the level of lower Belvedere (+75.0 m);
(c) 3 horizontal uni-axial seismometers at the level of upper Belvedere (+91.7 m), The uni-axial sensors installed in the lower and upper Belvedere are mounted on two opposite perimeter columns of the spire (Fig. 2b–c).

Each sensors triad is wired to one 24-bit digitizer, with the digitizers being connected to a switch for data transfer.

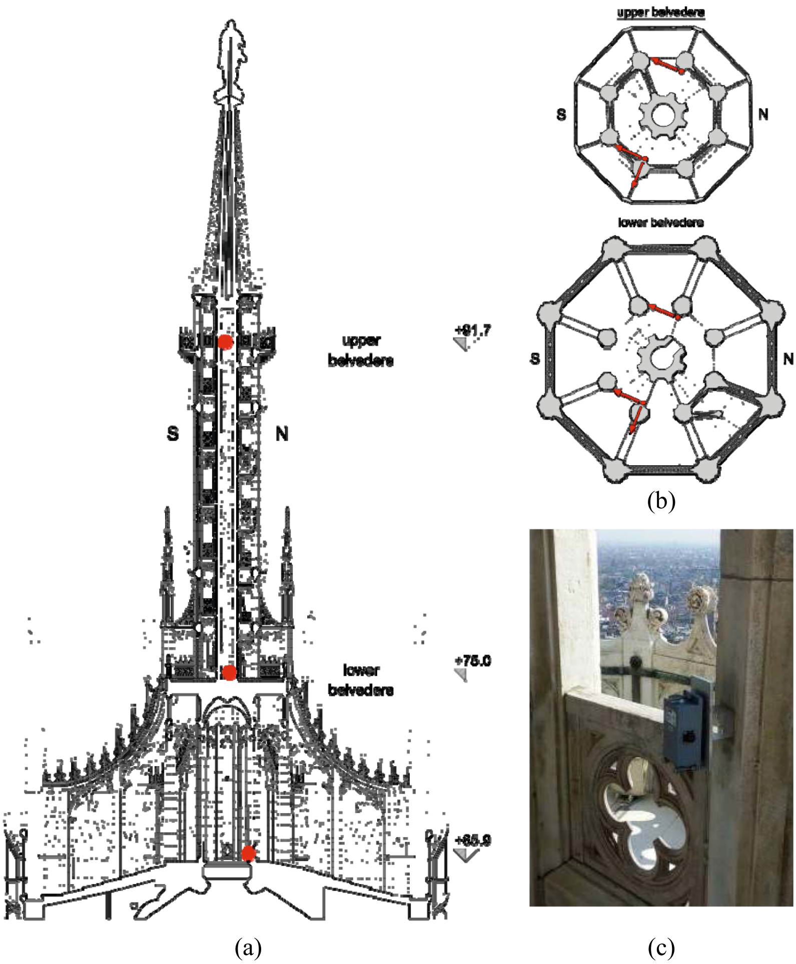


Fig. 2. Experimental setup of the dynamic monitoring system installed in the Main Spire: (a) in elevation and (b) in plan; exemplification of sensor mounting.

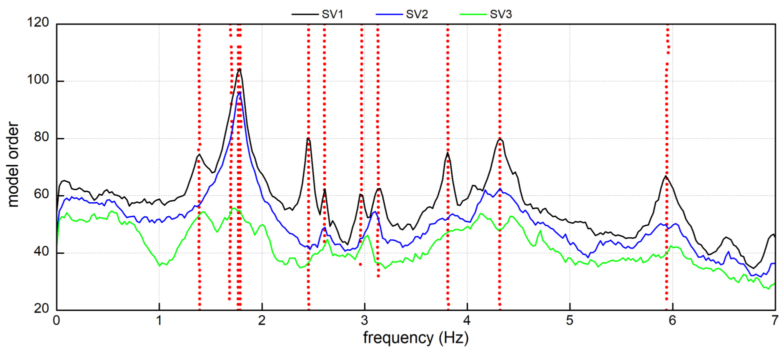


Fig. 3. Identification of natural frequencies via SSI-Cov to signals collected on the Main Spire.

3 Dynamic Charateristics of the Main Spire

A preliminary dynamic characterization of the Main Spire has been achieved through an Ambient Vibration Test on June 6th, 2018, whose experimental setup has been confirmed for the continuous monitoring system, active since October 16th, 2018 [3]. The modal parameters of the Main Spire are identified using a fully automated procedure, based on the covariance-driven Stochastic Subspace Identification (SSI-Cov) algorithm [8] and developed in previous studies [9].

The identification of resonant frequencies of the Main Spire is exemplified in the stabilization diagram of Fig. 3, which highlights a high density of principal modes in the frequency range 1–7 Hz, including both global modes of the entire Cathedral [3] and local modes of the spire.

The dynamic features associated to the local modes S1–S9 are reported in Table 1 in terms of resonant frequencies and damping ratios, whereas the associated mode shapes of selected modes are exemplified in Fig. 4. The sequence of the spire local modes usually appear in couples with similar mode shapes and close frequencies:

a) the first couple of modes, S1 (Fig. 7a) and S2 (Fig. 7b), involve bending in two orthogonal directions. The corresponding natural frequencies are equal to 1.77 and 1.79 Hz, respectively;
b) a second couple of modes, S3 (Fig. 7c) and S4 (Fig. 7d), are characterized by bending of the spire in two orthogonal planes, as well. Modes S3 and S4 exhibit natural frequencies of 2.45 and 2.61 Hz, respectively;
c) another couple of modes, S5 (Fig. 7e) and S6 (Fig. 7f), involve higher order bending of the spire associated to horizontal deflection of the base of spire. The associated natural frequencies are 2.97 and 3.13 Hz;
d) mode S7 (Fig. 7g), exhibiting higher order bending of the Spire, with the modal displacements of both Belvederes comparable in direction and amplitude. The corresponding natural frequency is 3.81 Hz;
e) finally, a couple of torsion modes S8 and S9 is identified at 4.32 and 5.94 Hz: mode S8 is associated to in phase rotation of the Upper and Lower Belvedere, whereas S9 to a rotation of the two levels in opposition or phase.

Table 1. Dynamic features of the Main Spire estimated via SSI-Cov (June 06th, 2018 18:00).

Mode Id.	f (Hz)	ζ (%)
S1	1.770	1.56
S2	1.790	1.15
S3	2.454	0.60
S4	2.610	0.41
S5	2.966	1.09
S6	3.128	1.28
S7	3.811	0.74
S8	4.318	1.16
S9	5.937	1.12

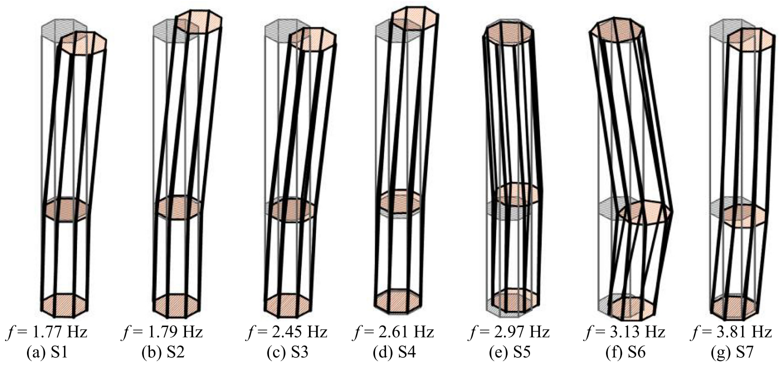


Fig. 4. Selected vibration modes of the Main Spire.

4 Evolution of Natural Frequencies

SHM projects of historic structures [3, 5, 7, 10, 11] are usually assisted by the monitoring of environmental factors that might affect the mechanical properties or the structural response. The assessment of environmental effect over the dynamic features of the structure at study can be a challenging task, though provides useful information on the structural arrangements, especially in masonry structures with a metallic reinforcement [11].

The description of the environmental conditions is provided by 3 couples of temperature sensors placed at 3 levels of the spire, as well as by a weather station installed in the upper Belvedere. Nevertheless, the temperature data measured at the 3 levels of the spire and by the weather station are highly correlated, so that only the last is adopted for SHM purposes.

Moreover, the amplitude of the collected velocities is strongly correlated to wind speed and also accounts for other sources of excitation (e.g. subway transits, maintenance activities on the Cathedral roof, far-field earthquakes, etc.). Hence, the root mean square of the velocities collected on the upper Belvedere is considered as an indirect measure of the level of dynamic excitation of the spire.

The results of the first year of dynamic monitoring of the Main Spire are summarized and discussed in this section. The time histories of the natural frequencies associated to local modes of the spire (S1–S9) are illustrated in Fig. 5, whereas the statistical description of the natural frequencies is summarized in Table 2, in terms of mean value (f_{ave}), standard deviation (σ_f), maximum (f_{max}) and minimum (f_{min}) values, and identification rate, which is defined as the ratio between number of identification over number the 1-h collected datasets.

Figure 5 highlights that the natural frequencies of the 9 local modes that were preliminarily identified (see Fig. 3) are identified with high occurrence during the first year and allows to draw the following conclusions:

(a) the identification rate ranges from 59.5% for mode S5 to 99.5% for S7;
(b) all identified frequencies evolve accordingly to regular patterns mainly driven by the temperature, tending to increase with decreased temperature. This trend is especially detectable for modes S1–S2 and S5–S9;
(c) the negative dependence of natural frequencies on temperature is a distinctive behavior of the Main Spire and of the Milan Cathedral [3], with this trend being very different from what generally reported in the long-term studies on masonry slender structures, i.e. towers [6–8, 10].

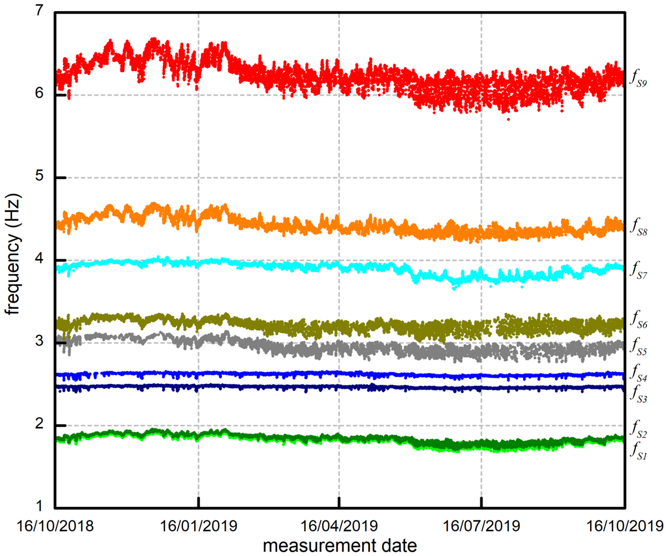


Fig. 5. Evolution of natural frequencies from October 16th, 2018 to October 15th, 2019.

Table 2. Statistics of identified frequencies from October 16th, 2018 to October 15th, 2019.

Mode	f_{ave} *(Hz)*	σ_f *(Hz)*	f_{min} *(Hz)*	f_{max} *(Hz)*	*id rate (%)*
S1	1.823	0.054	1.675	1.952	94.5
S2	1.845	0.055	1.705	1.994	95.9
S3	2.465	0.012	2.395	2.532	98.5
S4	2.614	0.016	2.534	2.688	81.0
S5	2.976	0.073	2.766	3.149	56.1
S6	3.220	0.064	2.978	3.355	75.3
S7	3.895	0.076	3.646	4.042	99.4
S8	4.435	0.095	4.213	4.744	99.3
S9	6.238	0.178	5.705	6.793	91.3

Nevertheless, the long-term and short-term influence between natural frequencies and outdoor temperature reveals peculiar behavior. As exemplified in Fig. 6a with reference to f_{S2}, some natural frequencies exhibit both negative correlation with seasonal (long-term) outdoor temperature, and positive correlation with hourly measured air temperature (short-term): the frequencies of some modes increase with increased temperature on a daily base, as it is exemplified in Fig. 6a with reference to an interval of 10 days. Such a dual dependency is conceivably driven by the effects exerted by the different materials that constitute the Main Spire. In more details, the thermal expansion of the Candoglia marble induces the closure of micro-cracks with increased temperature, leading to a stiffening of the spire and to the daily increase of the natural frequencies.

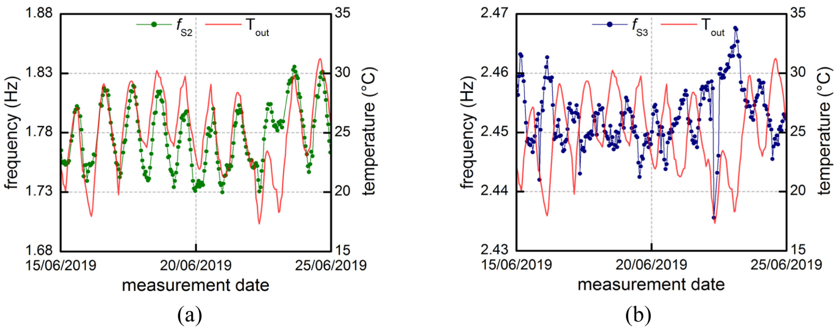


Fig. 6. Zoom of daily variations of air temperature and (a) f_{S2}, and (b) f_{S3}.

Conversely, the increase of seasonal temperature results in a slackening of the metallic confinement of the spire, leading to a global loss of stiffness and therefore to an overall decrease in the natural frequencies. The superposition of these two temperature-driven opponent effects conceivably explains the distinctive behavior of the frequency f_{S2}. It is worth mentioning that a similar complex dependence on temperature is observed for modes S1 and S5–S6 as well, whereas the frequency of modes S8–S9 continues to exhibit an overall negative dependence on temperature but the daily effects are less clear.

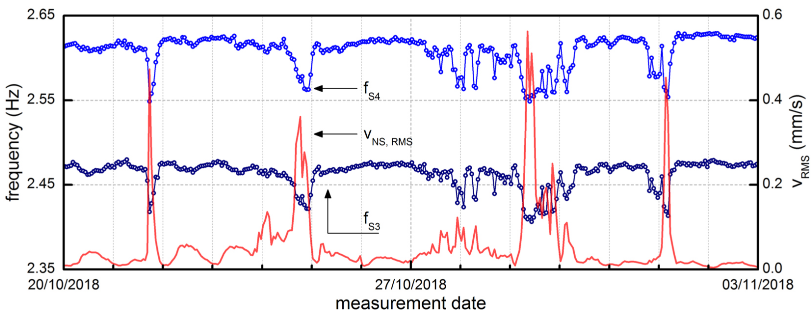


Fig. 7. Wind effects on frequencies f_{S3} and f_{S4}.

The natural frequencies of modes S3–S4 and S7 exhibit a simpler correlation with the air temperature, as exemplified in Fig. 6b for f_{S3}: both seasonal and daily variations of frequency and temperature are in phase opposition. Hence, the evolution of mode S3 seems to be conceivably driven by the stiffening effect exerted by decreasing temperature on the metallic elements of the spire.

In addition to the influence of temperature, it should be remarked that the excitation associated to wind gusts induce temporary drops of natural frequencies f_{S3} and f_{S4}. The typical correlation between frequency drops of f_{S3} and f_{S4} and the r.m.s. velocity (representing an indirect measure of the excitation level) is shown in Fig. 7 during a period of 10 days characterized by limited variations of the air temperature.

5 Conclusions

This study investigates the performance of a vibration-based Structural Health Monitoring (SHM) program to assist the preservation of an historic structure, the Main Spire of the Milan Cathedral.

The structure at study consists of a slender octagonal structure in Candoglia marble, supported by the *tiburio* of the Cathedral. The monitoring system includes seismometers (electro-dynamic velocity sensors) and temperature sensors at 3 levels of the Main Spire as well as a weather station at the top of the spire.

The SHM project of the Main Spire, comprises: (a) pre-processing and statistical analysis of the collected velocity signals; (b) continuous estimation of the modal parameters; (c) removal of the environmental influence over natural frequencies through PCA and (d) novelty analysis to detect slight changes in the statistical properties of the identified natural frequencies.

The analysis of the dynamic signatures collected over the first year of monitoring (i.e. from October 16th, 2018 to October 15th, 2020), lead to the following conclusions:

- The monitoring system and the application of automated operational modal analysis allows the identification and tracking of 9 local modes of vibration of the spire in the frequency range 1–7 Hz;
- The evolution in time of the natural frequencies during the first year of continuous monitoring reveals a distinctive correlation between resonant frequencies and temperature. In more details, all frequencies increase with decreased seasonal temperature and some of them (f_{S1}, f_{S2}, f_{S5} and f_{S6}) also exhibit a positive correlation with temperature on a daily basis, especially during the hot season;
- A couple of resonant frequencies (i.e., f_{S3} and f_{S4}) is also sensitive to the level of dynamic excitation associated with wind, with clear frequency drops occurring in correspondence to wind gusts.

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