Title:

Investigations on the dynamic behaviour of the Clock Tower in Lucca

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Abstract:

Introduction

The skyline of the ancient city of Lucca is characterized by a number of masonry towers and their belfries, many dating back to the medieval period. Among these monuments, the *Torre delle Ore* (Clock Tower) is one of the best known and most often visited, thanks to the peculiar shape of its bell chamber, which is clearly visible and recognizable throughout the entire historic centre. Built in the 13th century by local families, since the last decade of the 14th century the Clock Tower has been a civic building, taking its name from the big clock visible on its southern facade. The Clock Tower rises at the corner between the roads named Via Arancio and Via Fillungo, one of the most popular in Lucca’s historic centre. On 25 November, 2016 the ambient vibrations of the Clock Tower were monitored for a few hours via four seismometric stations (made available by the Seismological Observatory of Arezzo). This monitoring campaign allowed identifying some of the tower’s natural vibration frequencies and mode shapes [1]. A numerical model of the tower has been constructed via the NOSA-ITACA code [2] and calibrated in order to fit the experimental frequencies. This model has been used to simulate the influence of temperature variations on the tower’s frequencies [3].

In November 2017 a long-term ambient vibration monitoring experiment was begun by fitting six instruments along the tower’s height: four seismometric stations of the Arezzo Seismological Observatory, and two tri-axial accelerometers of the firm Assist in Gravitation and Instrumentation (AGI S.r.l.). The instrumentation worked on the tower up to March 2018. In the following, the dynamic identification of the Clock Tower is presented in detail, and the influence of the adjacent buildings on its dynamic behaviour investigated.

Figure 1. The Clock Tower in Lucca: upper part and ground floor

Methods

The Clock Tower is 48.4m high; it has a rectangular cross section of about 5.1x7.1m and walls of thickness varying from about 1.77m at the base to 0.85m at the top. Two barrel vaults are set inside the tower at heights of about 12.5 and 42.3m. The bell chamber, made up of four masonry pillars connected by elliptical arches, stands on the upper barrel vault and is covered by a pavilion roof constructed of wooden trusses and rafters. The adjacent buildings abut the tower on two sides along the Fillungo and Arancio roads for a height of about 13m and constitute asymmetric boundary conditions. With regard to the materials constituting the masonry tower, visual inspection reveals that the masonry from the base up to a height of 15 m is made up of regular stone blocks and thin mortar joints, as are the corners of the walls above this level, as well. The upper walls' central portions are instead made up of regular stone blocks and bricks, also with thin joints.

Figure 2 shows the sensors installed on the tower on 25 November 2016. During the three tests performed

(T1, T2 and T3), each lasting about one hour, two sensors were placed on the bell chamber and a third on the vault at 12.5m, which also corresponds to the height of the adjacent buildings' upper part, while the remaining sensor was moved to various different positions along the tower's height. In this paper we limit ourselves to analysing the data recorded during test T1, in which the fourth sensor was placed at the base of the tower in order to record ground vibrations. The T1 test data have been processed through the Complex Mode Indication Function (CMIF) Method [4], [5] implemented in TruDI [6]. This method belongs to the class of Experimental Modal Analysis (EMA) techniques and relies on singular value decomposition of the Frequency Response Function (FRF) matrix $H[j\omega]$ of the structure at each frequency ω. In particular, the CMIF is based on calculation of the eigenvalues of the matrix $H[j\omega]^H H[j\omega]$ for each ω. In the case of experiment T1, the three signals recorded at the tower's base represent the system's input, while those from the remaining instruments are the system's output.

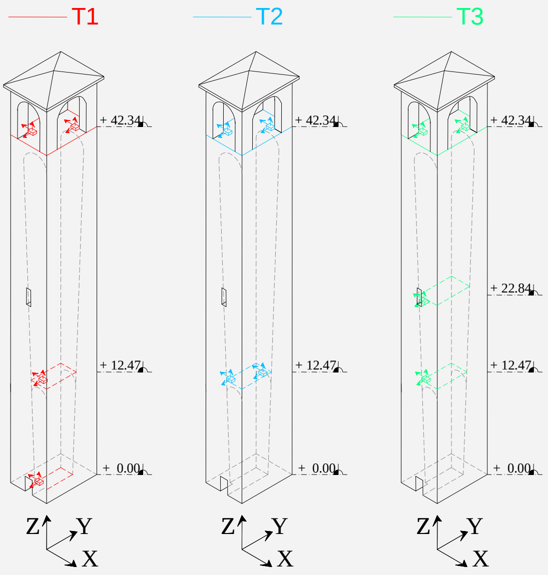

Figure 2. The Clock Tower in Lucca: sensor arrangement during the 25 November experiment

Results

Figure 3 shows the three eigenvalues of $H[j\omega]^H H[j\omega]$ calculated via the TruDI code for test T1. The first curve (blue) presents four peaks, at 1.05 Hz, 1.3 Hz, 4.2 Hz e 4.5 Hz, which represent the natural frequencies of the tower. The peak at 4.2 Hz is also visible on the second curve (green), and may represent a repeated eigenfrequency of the system. With regard to the tower's mode shapes, the first two frequencies are associated to flexural mode shapes, while the second two involve torsional movements of the tower [1]. The first curve in figure 3 also highlights the frequency around 3 Hz. This frequency is clearly visible in the FFT of the signals recorded by the sensor at the tower's base, in particular along Via Fillungo (the x direction in fig. 4), and in those recorded at the 12.47m level. Instead, it is absent in the signals measured on the bell chamber. This phenomenon could be explained by interactions of the tower with the adjacent buildings. To validate this hypothesis, on 17 November 2017 a sensor was installed for a few hours in a flat in the building adjacent to the tower along Via Fillungo (Fig. 5). The results of these measurements are summarized in Fig. 6, which plots the FFT of the signals recorded in the flat. The 3 Hz frequency clearly appears in the x direction (along Via Fillungo), thereby lending support to the hypothesis that this frequency belongs to the building. The tower's frequencies are also recognizable in the building's vibrations, in particular at 1.05 Hz along x, and 1.3 Hz along y and z.

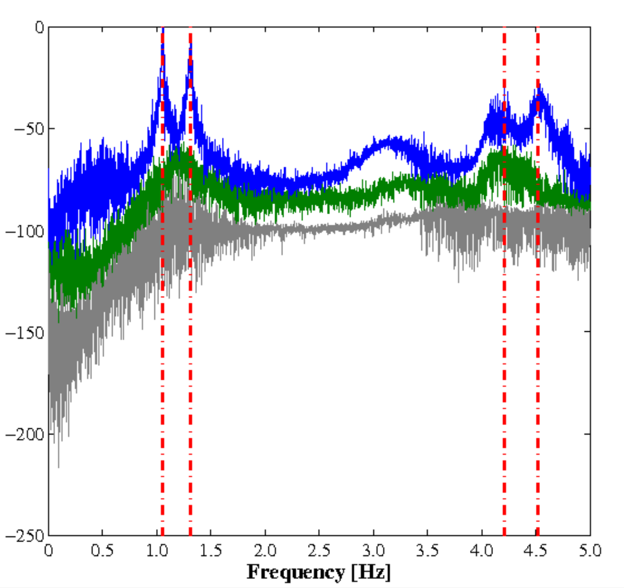

Figure 3. Eigenvalues of the matrix $H[j\omega]^{H}\,H[j\omega]$on a log-magnitude scale.

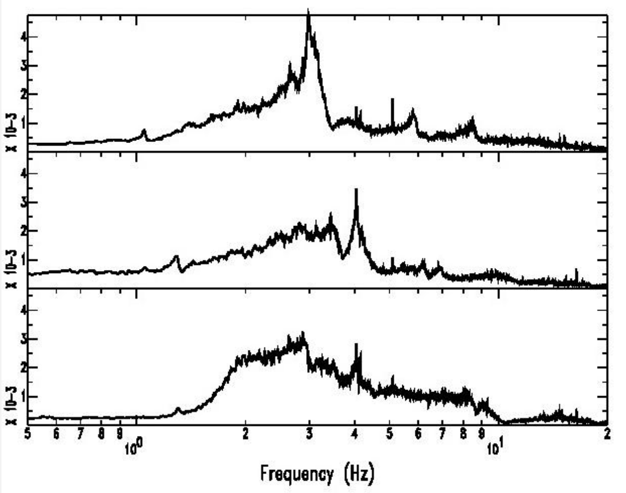

Figure 4. Fast Fourier Transform amplitude of signals recorded at the tower’s base during test T1, along *x* (top), *y* and *z*.

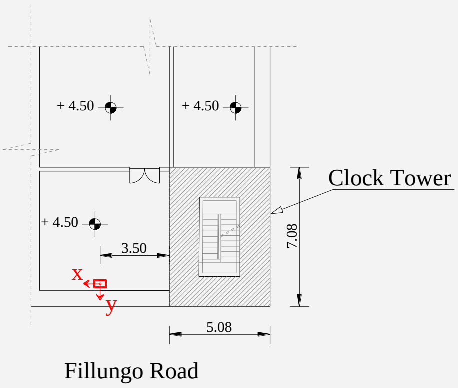

Figure 5. Position (red) of the sensor installed in a flat adjacent to the Clock Tower.

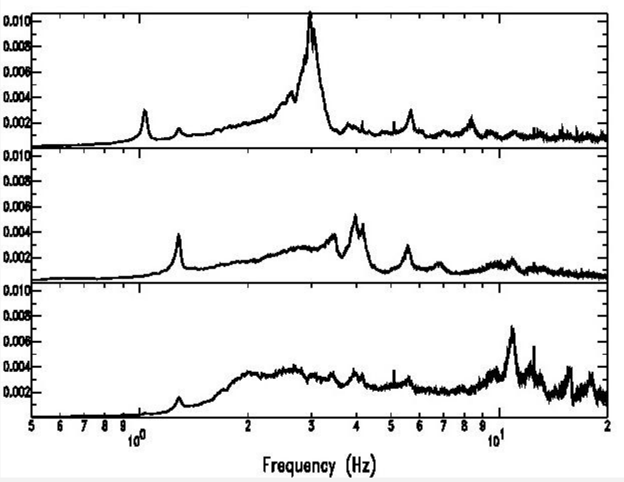

Figure 6. Fast Fourier Transform amplitude of signals recorded in a flat adjacent to the tower, along *x* (top), *y* and *z*.

Conclusions and Contributions

The measurement campaign described in this contribution has allowed us to study and identify the dynamic properties of the medieval Clock Tower in Lucca. Measured velocities were processed via suitable modal identification algorithms, and the influence of the adjacent buildings' vibrations on the dynamic behaviour of the tower investigated as well.

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