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The influence of environmental parameters on the dynamic behaviour of the San Frediano bell tower in Lucca

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ABSTRACT

This paper aims at assessing the influence of environmental parameters on the modal characteristics of age–old masonry constructions. The results of a long–term ambient vibration monitoring of the San Frediano bell tower in Lucca (Italy) are reported. The tower, dating back to the 11th century, has been fitted along its height with four triaxial seismometric stations, which were left active for about one year. Data from the monitoring system have been processed via the Stochastic Subspace Identification Method in order to identify the tower's modal characteristics and their variations over the year. The dependence of the tower's frequencies on the ambient temperature was first studied and simulated via simple auto–regressive models. Then, some output–only models based on the principal component analysis (PCA) were applied, under the hypotheses of both linear and non-linear (Kernel PCA) dependence of the natural frequencies on the unknown environmental parameters. The results indicate PCA to be an effective tool for detecting changes in the dynamic characteristics of masonry constructions.

1. Introduction

Measuring the vibrations of masonry towers is a common practice for assessing their dynamic behaviour. The first efforts date back to the 1970s [8], when researchers began to investigate the inertia forces induced on bell towers by the swinging bells. In [25] the authors presented the results of an experimental campaign conducted on 19 church towers in England, in which the towers' accelerations during bell-swinging were measured and their fundamental frequencies identified, while in [10] the effects of bell–swinging on the dynamic behaviour of a masonry tower in Spain are analysed. In addition to the bells actions, masonry towers are subjected to a number of vibrations sources, such as traffic, micro–tremors, wind and earthquakes. The availability of even more sensitive instruments to detect towers' movements is allowing researches and engineers to conduct accurate long–term monitoring campaigns. In fact, ambient vibration monitoring can provide important information on the structural health of old masonry constructions, as it is a non-destructive technique able to capture the most important features of their dynamic behaviour, such as natural frequencies, damping ratios, mode shapes and wave propagation velocities. Once the influence of environmental factors has been accounted for, changes in these dynamic properties over time can represent effective structural damage indicators.

The literature contains few reports on long–term ambient vibration recordings on monumental buildings. Among these, paper [17] reports on the vibrations of the Mogadouro Clock Tower and the church of the Monastery of Jeronimo in Portugal, [2] studies the Garisenda and Asinelli towers in Bologna (Italy), [6] describes the dynamic monitoring of the tower of the church of San Vittore in Arcisate (Italy) and [5] deals with ambient vibration testing of the bell tower of the cathedral of Monza. Dynamic monitoring of Gabbia tower in Mantua (Italy), reported in [7,23], furnishes data before and after the earthquake that struck the North of Italy in May 2012: a slight permanent variation in the natural frequencies of the tower has been observed after the seismic event. In all these examples, the influence of environmental parameters such as temperature and humidity, on the measured natural frequencies of the monuments has been observed and modelled via auto–regressive models. Finally, in [26–28] authors report on the monitoring of the San Pietro bell tower in Perugia, study the environmental effects on its natural frequencies and propose procedures to detect damage.

The environmental parameters affect the dynamic behaviour of monumental buildings in a peculiar way, which seems to be different

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from that of concrete, steel and prestressed concrete structures [14]. For example, in the cases cited above the natural frequencies of the monuments increase with temperature. Another issue arises regarding recognition of the most effective configuration of the ambient sensor network able to capture the correlation between the monument's dynamic properties and the external environment. In addition, in most cases the environmental parameters are measured in a very limited number of points on the structures. For these reasons, output–only procedures can prove to be useful. The term "output–only" means that, given a system subjected to unknown inputs (ambient vibrations and other environmental factors), only the damage–sensitive features (natural frequencies, for example), which constitute the system's output need to be measured for the system to be characterised. A crucial point is that the variations in environmental conditions are typically much slower than the structural vibrations. Thus, for example, changes in temperature and humidity have daily or seasonal frequency, while the highest structural eigenperiods are in the order of one or few seconds. This enables estimating the damage–sensitive features of the structure via short sequences of measured data, during which the structure behaves as a linear time–invariant system, and then considering these estimated quantities as the outputs of a global model, whose input are the unknown environmental parameters.

In this paper we present the results of long–term ambient vibration monitoring of the San Frediano bell tower in Lucca. The tower has been fitted with four three–axial high–sensitivity seismometric stations, left on the monument for about one year. The velocities recorded by the instruments have been used for the dynamic identification of the tower. The bell tower and its monitoring are described in Section 2. A preliminary experimental campaign on the tower was conducted in May 2015. The results have been presented in [1], where the tower's natural frequencies, mode shapes and modal damping ratios have been estimated from a five day dataset via the Stochastic Subspace Identification (SSI) Method [15,19], implemented in the MACEC [20] code. In [1] a finite–element model has also been built with the NOSA–ITACA code [4,12,16] and applied to estimate the mechanical properties of the tower's constituent materials. The results presented in [1] are briefly summarized at the end of Section 3 herein, which also describes the improved identification of the tower's mode shapes obtained by merging data from different sensor layouts. Most of Section 3 is devoted to data analysis. An automated SSI procedure is applied to the entire monitoring period, after dividing the velocities dataset into many one hour long sequences. During the early hours of 24 August 2016, the signal of the Amatrice earthquake, that struck central Italy with a 6.0 magnitude, was also recorded on the tower. Although Lucca is about 400 km far from Amatrice, the signal of the earthquake was clearly detected by the sensors, with velocities on the same order of those induced by the swinging of the bells. No significant damage was observed on the tower as a result of the seismic event.

Section 4 focuses on the influence of environmental parameters on the dynamic properties of the tower. Unlike [5,7,27], where only linear models are used, here a nonlinear approach is followed as well. In Section 4.1 some Auto–Regressive eXternal input (ARX) models are applied by taking the tower's natural frequencies as output and the air temperature measured in Lucca's historic centre as input. Then, in Section 4.2, the procedure described in [21], which makes use of the Gaussian kernel principal component analysis (kernel PCA) to study a post–tensioned concrete bridge, is applied in order to identify output–only linear and nonlinear environmental models. These models, focused on novelty detection in signal processing, are able to automatically detect anomalies in the tower's dynamic response. They are applied to the recorded data by using different training periods and, in particular, before and after the Amatrice earthquake, in order to assess the tower's structural integrity after the event. Some simple damage scenarios are also simulated, in order to test the models' ability to detect structural damage on the structure. The results indicate that in the case under examination performances of linear PCA and kernel PCA are comparable.

Fig. 1. The Basilica of San Frediano in Lucca (Italy). On the left, the San Frediano bell tower.

Although continuous monitoring of structures is a common practice, data available from long–term measurements on historical buildings are quite scarce. Thus, the information collected and analysed in this paper on the changes in the dynamic properties of the bell tower over one year, will enhance our understanding of the dynamic behaviour of such constructions and allow for detecting any structural damages they may undergo.

2. The San Frediano bell tower and the monitoring system

The Basilica of San Frediano (see Fig. 1) dates back to the 11th century. It is one of the most fascinating monuments in Lucca, much of its fascination being due to the marvellous mosaics that adorn its façade, which glistens spectacularly in the light of the rising sun. The church's bell tower is one of the best preserved in Lucca's historic centre. It is 52 m high, with walls varying in thickness from about 2.1 m at the base to 1.6 m at the top. The tower is entered through a masonry staircase leading from the street level to the first floor, which is formed by a masonry vault set at a height of about 8.6 m (Fig. 2). From this level, a stone staircase running along the inner perimeter provides access to the terminal section of the tower, about 40 m high, which houses the bells. The bell chamber is separated from the rest of the structure by a stiff masonry vault, which has been fitted with 4 steel tie rods of rectangular section. Over the vault, at about 43 m, there is a walkable wooden floor, which makes it possible to reach the bells. No rigid diaphragms are present inside the tower between the two vaults: the structure's section is not stiffened for about 30 m's height. The tower bears openings on all sides and is covered by a pavilion roof made up of wooden trusses and rafters in a very poor state of maintenance. The San Frediano Basilica adjoins the tower on two sides for about 13 m of its height. Although little information is available on the history of the bell tower, the numerous modifications made to the structure over time are clearly visible. In particular, the upper part of the structure, now hosting the bell chamber, seems to have been built later than the rest of the structure. The same appears for the bifora and trifora windows along the tower. With regard to the mechanical characteristics of its constituent materials, no experimental information is available at the moment. On visual inspection, the masonry seems to be made up of regular stone blocks at the base, while quite homogeneous brick masonry is visible in the upper section, apart from the central part of the walls, where the masonry between the windows is made up of stone blocks.

Between May and June 2015 the tower was instrumented with four SARA triaxial seismometric stations (Fig. 3). Each station was equipped with a SL06 24-bit digitizer coupled to a SS20 seismometer