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Dynamic characterization of a bell tower by interferometric sensor

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Abstract

The dynamic characterization of a medieval bell tower, forced by its own bell is obtained by using a newly developed interferometric sensor. The displacement of the tower is remotely detected, without installation of contact sensors and the use of a cumbersome vibrodyne for structure excitation. The measurement technique demonstrated in this paper allows heritage bell towers to be monitored in a simple and rapid way.

Keywords: Radar; Remote sensing; Interferometry; Dynamic monitoring; Structural test

1. Introduction

The dynamic characterization of architectonic structures is of paramount importance in order to survey their conservation status, and possibly to plan maintenance or remedial works [1]. As the resonance frequency of a structure is directly related to its rigidity, its measured value can be employed to evidence lesions that could have compromised the structural integrity [2,3]. In particular for bell towers, the lowest resonance frequency has to be quite higher than the frequencies stimulated by bell movement: a decrease in the resonance frequency can make the pealing of bells dangerous.

Dynamic tests are usually implemented by networks of accelerometers installed on the structure [4]. The placement of such sensors is the most time consuming and expensive operation, as monitoring of large structures can require the use of costly scaffolding. Settling the optimal sensor placement is a common problem encountered in many engineering applications and is a critical issue in the implementation of an effective structural health monitoring [5]. Furthermore, in a number of situations, placing of contact sensors may be not possible: this is the case, for example, in buildings with symptoms of impending collapse. Laser sensors [6] have been proven often unpractical for in-field applications. A proposed solution is to use a global positioning system (GPS) [7], but its accuracy is not good enough to meet the strictest measurement requirements.

Conventional techniques for dynamic characterization of structures make use of pseudo-random noise (like wind or vehicular traffic [8]) or frequency sweep vibrodynes as dynamic sources.

The employment of natural sources (wind, vehicular traffic) as solicitation is usable only for structures elastic enough to give appreciable deflections. Otherwise, suitable exciters, like vibrodynes, must be installed on the structure, with consequent complications and costs.

In previous papers [9,10], the authors demonstrated the use of a high-speed interferometric radar as remote sensor of displacements not requiring the installation of contact sensors on the structure.

The use of an interferometric radar to detect the dynamic transfer function of a bell tower excited by its own bell is described in this paper. Unfortunately, a bell is not a spread spectrum source but rather a non-linear oscillator that produces harmonics [11,12]. The aim of this work is to

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exploit this excitation for obtaining information about the dynamic transfer function of the tower and possibly its natural frequency.

2. Action of bells

The action induced by the bells on the structure during their pealing depends mainly on the bell characteristics (size, weight) and on amplitude of oscillations [11,12]. A forced oscillating bell is a non-linear oscillator, so the action induced by the bell presents harmonic components that increase with oscillation amplitude. Therefore, by using a bell as forcing stimulus, the dynamic transfer function of the structure can be sampled only at the fundamental frequency of the bell and at its harmonics. It should be noted that in a number of cases, the spectral content of a forcing bell could be obtained in analytic way, if period, shape and mass are known [11].

3. Interferometric sensor

The displacement vs. time of the tower was measured by using an innovative sensing instrumentation able to provide the absolute deformation of the structure by operating at distance. The equipment is basically a coherent radar, designed by the authors and described in previous works [9,10]. It is able to provide range discrimination with range bin given by the following equation:

$$\Delta R = \frac{c}{2B} \tag{1}$$

with c being the speed of light and B the radar bandwidth.

As the equipment is a coherent radar, the range profiles keep the phase information. Thus, two range profiles acquired at different times exhibit phase differences depending on the motion of the targets along the radar line-of-sight. The phase shift $\Delta\varphi$ of the pixel relative to a specific target in the scenario is related to its range displacement Δr, occurred in the time elapsed between the two images, through the following relationship:

$$\Delta r = \frac{c}{4\pi f_c}\Delta\varphi \tag{2}$$

with f_c being the band center frequency.

The interferometric sensor has been implemented as a portable equipment, powered by a battery pack and held by a tripod. It radiates at 16.75 GHz center frequency with 350 MHz bandwidth, and is controlled via the USB port of a common portable PC. Design specifications on phase accuracy are suitable for measuring displacements with a range accuracy better than 0.1 mm.

4. Measurement setup

A measurement campaign has been carried out on the bell tower of the church of Pratolino, a small town near Florence, Italy. It is an ancient XV century church that suffered a number of restorations, and needs a periodical monitoring. The bell tower is a stone structure 20 m high, with square base of 5 m side. The architectonic design of the church with its bell tower is shown in Fig. 1.

The radar equipment has been placed at two different positions in order to detect tower displacements along the two orthogonal directions.

The measurement along the north–south direction (position 1 in Fig. 2) was carried out positioning the instrument on a tripod at 5 m from the north side of the tower (see picture in Fig. 3) with such an elevation angle as to illuminate the major part of the vertical extension of the tower.

The measurement along the east–west direction (position 2 in Fig. 2) was carried out from the west side that is partially hidden by the church: the other side of the tower was inaccessible. This position (position 2) is approximately 39 m from the west side of the tower, allowing only the highest part of the tower to be visible (see picture in Fig. 4).

The bells, labelled with A–C, are positioned as shown in Fig. 2. The pealing direction of each bell is indicated in the figure.

4.1. Measurements from position 1 (N–S direction). C-bell pealing

The radar provides a range plot of the scenario illuminated by the sensor. Fig. 5 shows the range plot obtained from position 1. In the range 8–22 m several peaks

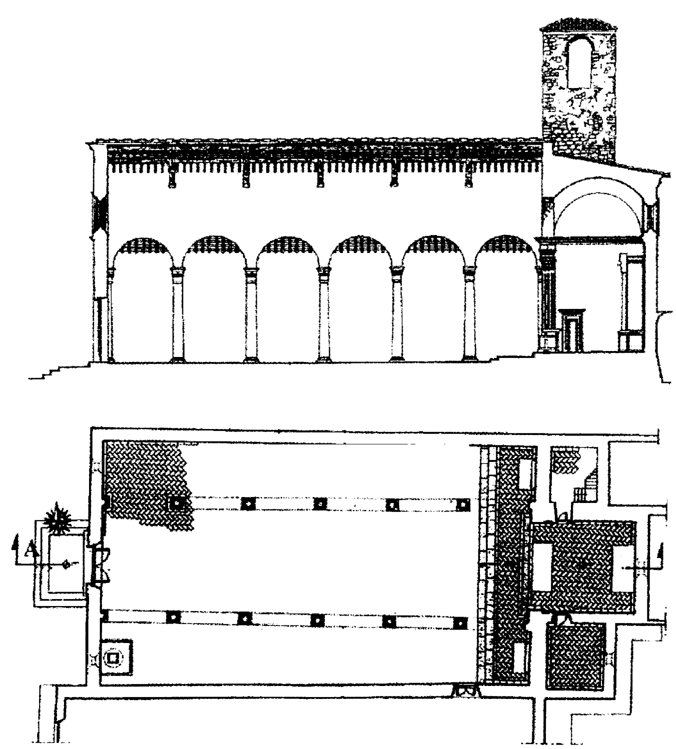

Fig. 1. Architectonic plan of the church with its bell tower.