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Survey and testing through interferometric radar: applications to Cultural Heritage and public utilities

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Abstract

This paper report working principle and several case studies of an innovative radar technique able to operate as diagnostic and monitoring tool on large structures such as buildings, towers, bridges.. The most attractive feature of this technique is that operates without the need of accessing the structure to install sensors or optical targets.
A number of applications in the field of Cultural Heritage monitoring and public utilities testing are reported.

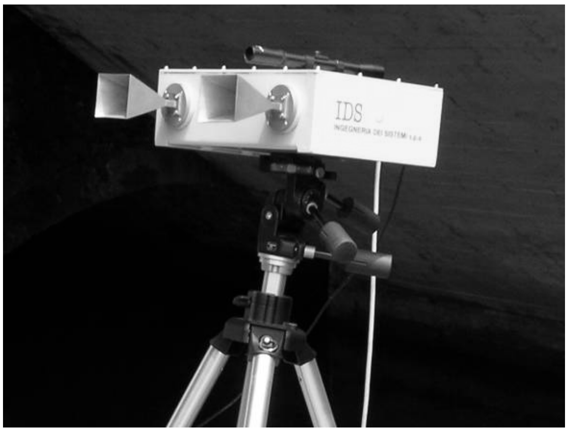
1. Introduction

The static and dynamic characterization of architectonic structures is of paramount importance, in particular when they are part of the Cultural Heritage.
The conventional monitoring tools of structural displacements of buildings are represented by a variety of techniques(1), such as networks of optical targets installed over the structure, strain gauges to detect deformations, collimation nets to detect displacements, inclinometers to measure rotations. Such sensors are accurate and reliable, but require to be in contact with the structure to be surveyed, and information is localized to the specific point where the sensor is positioned. Settling the optimal sensor placement is a common problem encountered in many engineering applications and is a critical issue in the implementation of effective structural health monitoring(2). Furthermore, the monitoring of large structures can give rise to accessibility problems, often requiring the use of costly and cumbersome scaffolding. In a number of situations, the placing of contact sensors may be not possible; this is the case, for example, in buildings with symptoms of impending collapse after a seismic shock or a blast. The capability of performing in-service monitoring is a key requirement for planning survey campaigns aimed at the early identification of structural problems in order to enable low-cost maintenance remedial actions to be taken.

In the last years the research group of the author has developed portable high speed radar systems able to perform both static and dynamic testing of large structures, as bridges, bell-towers, buildings, dams, wind towers..[3-11]
These systems operate at distance, without installation of sensors on the structure, that can be kept in-service during the measurements. Because its high rate acquisition (up to 100Hz) and its long term stability it is able to perform both dynamic and static testing, by providing information about natural frequencies, modal shapes, elasticity, long term deformation, ..
In this paper the author reviews the working principle and reports several examples of applications.

2. The equipment

The microwave interferometer (Figure 1) is a radar sensor able to simultaneously monitor the response of several points belonging to a large structure, providing for each point the displacement response.



Operational characteristics	
Maximum operational distance (for minimum 40Hz sampling frequency	500.00 m
Maximum sampling frequency	100.00 Hz
Displacement sensitivity (accuracy)	0.01 mm
Operative weather condition	All

Figure 1: View of the microwave interferometer

The equipment has been developed by a cooperation between University of Florence and a private company, IDS SpA of Pisa, Italy. After several years of studies and research, since 2006 the sensor is a commercial product.

The working principle of the sensor is based on two well-known radar techniques:

a) the Stepped-Frequency Continuous Wave (*SF-CW*) technique, allowing the system to resolve the scenario in the range direction, i.e. to detect the position of target surfaces placed at different distances from the sensor;
b) the Differential Interferometric technique, allowing the system to measure the displacements of the structure illuminated by the antenna beam by comparing the phase information of the back-scattered electromagnetic waves collected in different times.

2.1 The SF-CW technique

The capability to determine range (i.e. distance) by measuring the time for the radar signal to propagate to the target and back is surely the most important characteristic of radar systems.
Two or more targets, illuminated by the radar, are individually detectable if they produce different echoes. The *resolution* is a measure of the minimum distance between two targets at which they can still be detected individually. The *range resolution* refers to the minimum separation that can be detected along the radar's line of sight.
The *SF-CW* technique is based on the synthesis and transmission of a burst of *N* monochromatic pulses equally and incrementally spaced in frequency.
At each sampled time instant, both *I* (In-phase) and *Q* (Quadrature) components of the received signals are acquired so that the resulting data consist of a vector of *N* complex samples, representing the frequency response measured at *N* discrete frequencies. By taking the Inverse Discrete Fourier Transform (*IDFT*) the response is reconstructed in the time domain of the radar.
In this sensor, the *SF-CW* technique has been implemented to obtain a range resolution of 0.50 m, independently from the maximum operative distance; in other words, the sensor is able to distinguish two different targets if their relative distance is greater than 0.50 m. The range resolution area is termed *range bin*.

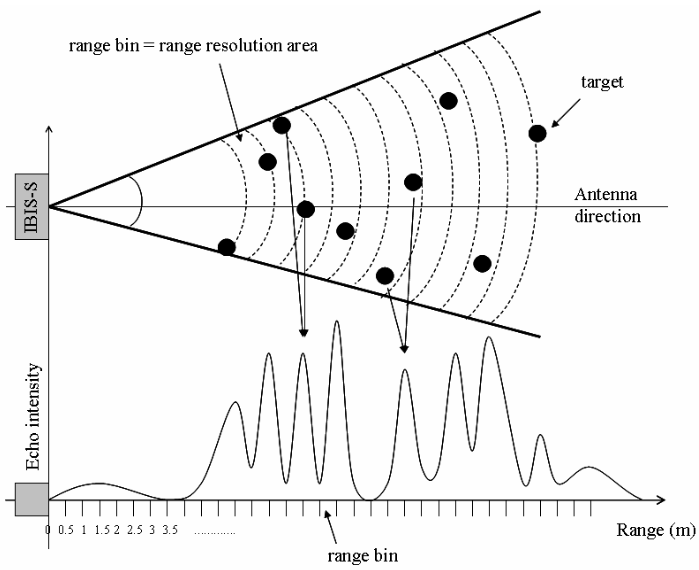


Figure 2: Range resolution concept.

The concept of range profile is illustrated in Figure 2; peculiarly Figure 2 shows an ideal range profile obtained when the radar transmitting beam illuminates a series of targets at different distances and different angles from the system.

2.2 Differential Interferometry technique

Once the range profile of a structure has been determined at uniform sampling intervals, the displacement response of each range bin is evaluated by using the Differential Interferometry technique. Interferometry is a powerful technique that allows the displacement of a scattering object to be evaluated by comparing the phase information of the electromagnetic waves reflected by the object in different time instants

Generally speaking, when of a target surface moves with respect to the sensor a phase shift arises between the signals reflected by the target surface. Hence, the displacement of the investigated object can be determined from the phase shift measured by the radar sensor. The radial displacement d_p (i.e. the displacement along the direction of wave propagation) and the phase shift $\Delta\varphi$ are linked by the following:

$$d_p = \frac{\lambda}{4\pi}\Delta\varphi \qquad (1)$$

where λ is the wavelength of the electromagnetic signal.

3. Monitoring of Cultural Heritage

A considerable amount of old buildings are part of Cultural Heritage, therefore their conservation is a priority without regard of their serviceability. Indeed, in the last years, the demand of monitoring tool for assessing the conservation status of buildings is dramatically increased. Here several applications of remote monitoring of Cultural Heritage are reported.

3.1 Goitto's bell-tower

The vibration of the world-known Giotto's tower in Florence, excited by its own bell tolling, has been measured from an about 160 m distant point of observation.[7]

The tower was built by Giotto in fourteenth century, and is one of the most famous monuments of the world cultural Heritage. It has a square base of 14.45 m side, and a height of 87.40 m. The aim of the test was to detect the displacements of the tower vibration caused by tolling of its bells. The equipment was installed on a balcony at the higher floor of a building at over 160 m distance from the tower (Figure 3).

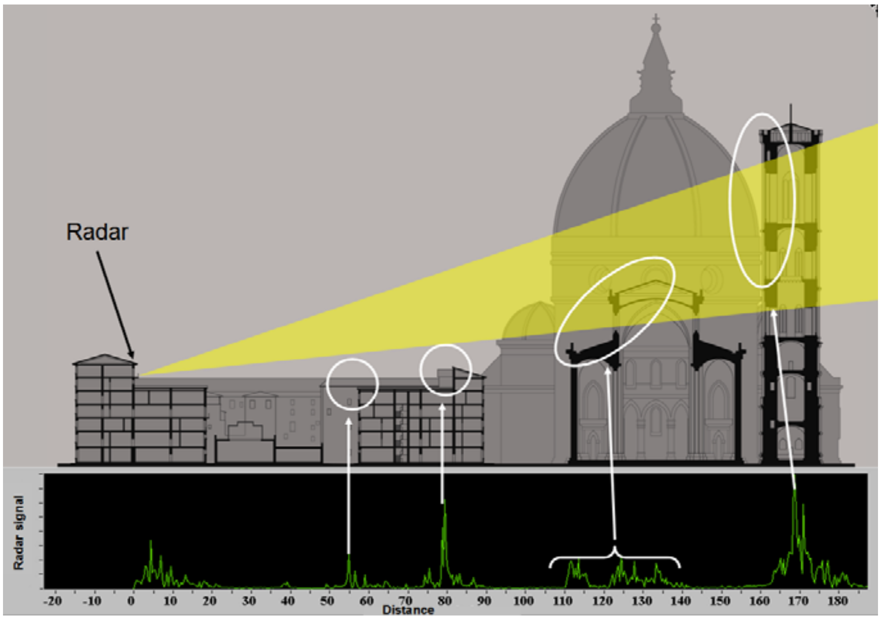


Figure 3: Sketch of Giotto's tower monitoring

The lower part of Figure 3 shows the range-domain radar image. The strong signal at 110 m is due to the side wall of the cathedral, that is almost perpendicular to the line-of-sight. The signal reflected by the Giotto's tower at different heights lies between 160 and 180 m.
The upper image in Figure 4 shows the range displacement in time of the target on the tower labelled in Figure 3. The lower image in Figure 4 shows the FFT of the signal: the frequency peak corresponds to the cadence of the tolling.

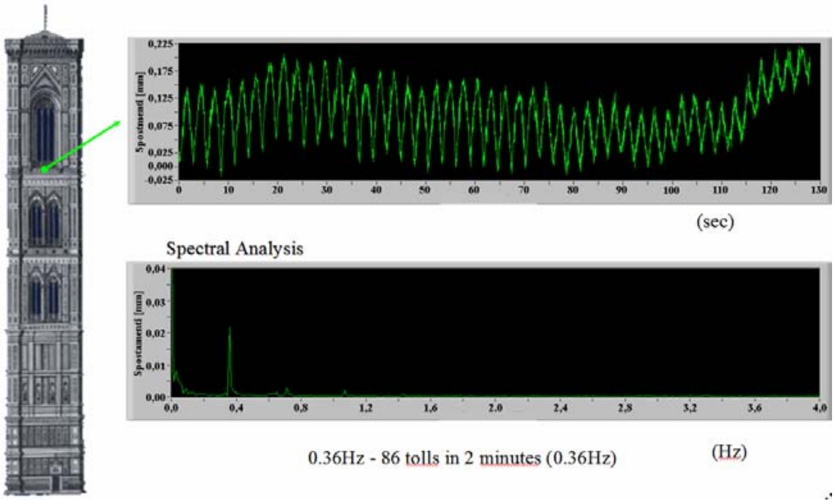


Figure 4: Measured displacement of Giotto's tower

3.2 Arnolfo's -tower

Another very famous tower in Florence is the Arnolfo's tower that is located over the historical town hall. The measurements has been performed from the place in front of the building and also from the roof of the town hall. The results are reported in Figure 5. As the base in not square, the tower has two different natural frequencies as shown in figure.

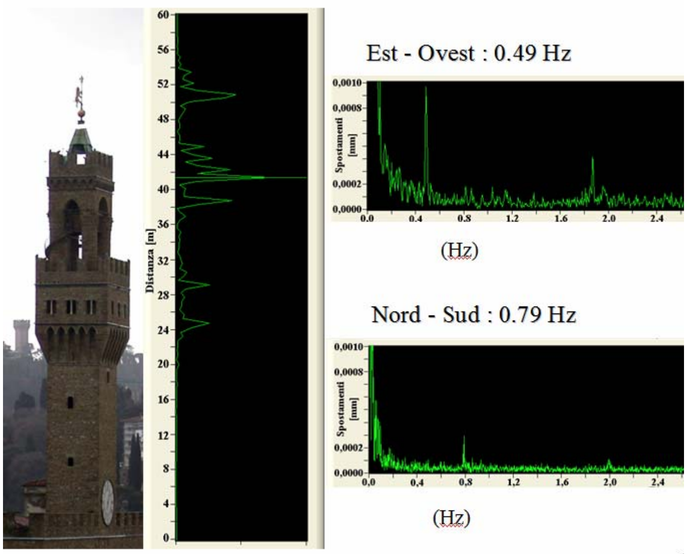


Figure 5: Radar image and measured natural frequencies

3.3 Long distance monitoring ("Landscape mode")

A very attractive characteristic of this instrument is its capability to perform measurements in "landscape mode", i.e. at great distance from the building under test. In order to verify this capability, the radar was mounted on the walls of Forte Belvedere, placed in a hill near the town centre of Florence, and pointed toward Giotto's Bell Tower and Arnolfo's Tower (Figure 6). The angle between the directions of the two towers (7 degrees) was smaller than the half power beam width of the antennas (13 degrees), than was possible to see both structures from that position. The distance from Giotto's Bell Tower was 995 m and from Arnolfo's Tower was 610 m. The suitable radar settings for this application was: 4 km of non-ambiguous range, 5 m of range resolution (pixel dimension of radar image) and 56 Hz of sampling rate.

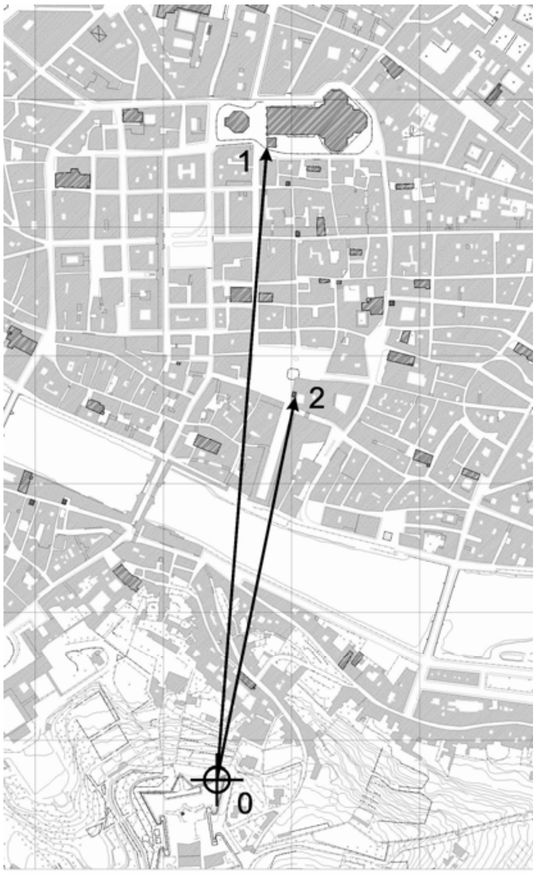


Figure 6: Map of Florence including the arrangement of the measure: 0 is the radar position; 1 is the Giotto's Bell Tower position; 2 is the Arnolfo's Tower position.

The signal-to-noise ratio for long distance measures is very low, so we computed the frequency domain analysis of phase signal for a long time measure (about 1 hour), in order to bring down the uncorrelated flat noise.
In Figure 7, are visible two high peaks in range profile (radar image), corresponding to backscattered signals from the two towers.
The FFT of phase signal of Arnolfo's Tower pixel, shown in Figure 8, points out a resonance frequency of about 0.81Hz.

Same analysis for the Giotto's Bell Tower (Figure 9) points out a resonance curve centred at 0.64 Hz.

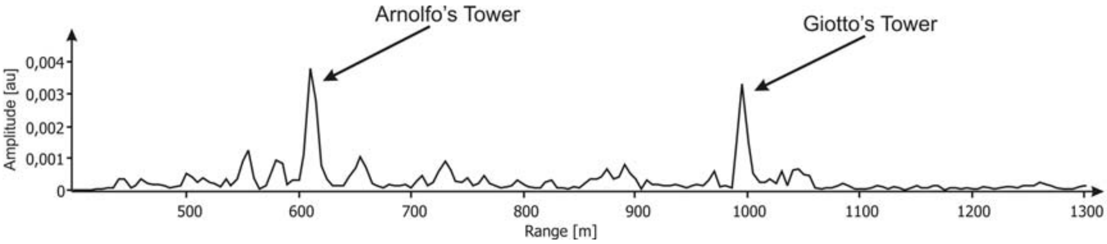


Figure 7: Radar range profile with two peaks of Arnolfo's Tower and Giotto's Tower

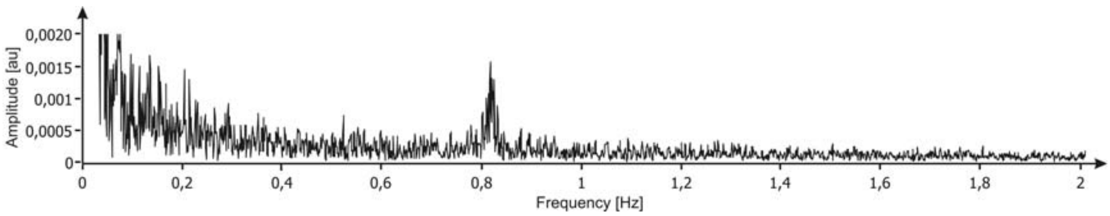


Figure 8: FFT of phase signal of the pixel corresponding to Arnolfo's Tower

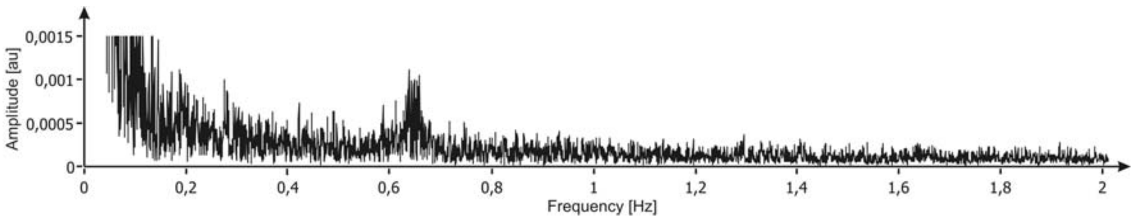


Figure 9: FFT of phase signal of the pixel corresponding to Giotto's Bell Tower

3.4 Pratolino's church

The use of an interferometric radar to detect the dynamic transfer function of a bell-tower excited by its own bell has been tested on a historical bell-tower near Florence.[(10)]
A bell is not a spread spectrum source but rather a non-linear oscillator that produces harmonics. Anyway, just the harmonics can be employed for obtaining information about the dynamic transfer function of the tower and possibly its natural frequency.
With this aim, 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 20m high, with square base of 5m side. The radar equipment has been placed at two different positions in order to detect tower displacements along the two orthogonal directions (see Figure 10).
In order to properly analyze the temporal behaviour of the spectral components, the joint time-frequency analysis is a valuable mathematical tool; thus, a Short Time Fourier Transform (STFT) by using a mobile window of 25 seconds was performed. The result is shown in Figure 11. The harmonic behaviour is well-evident.

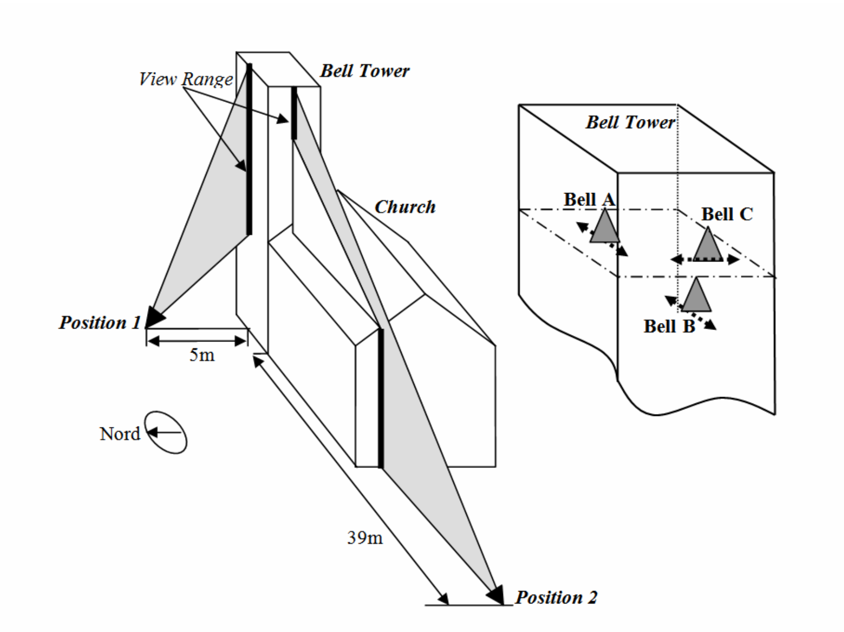


Figure 10: geometry of measurement of Pratolino's bell tower

Finally, in order to evaluate the transfer function of the structure, it is necessary to know the spectrum of the forcing stimulus. The most direct way is to install an accelerometer on the bell. The transfer function of the tower can be calculated simply by the ratio between amplitude of the displacement and amplitude of the forcing stimulus at the harmonic frequencies.

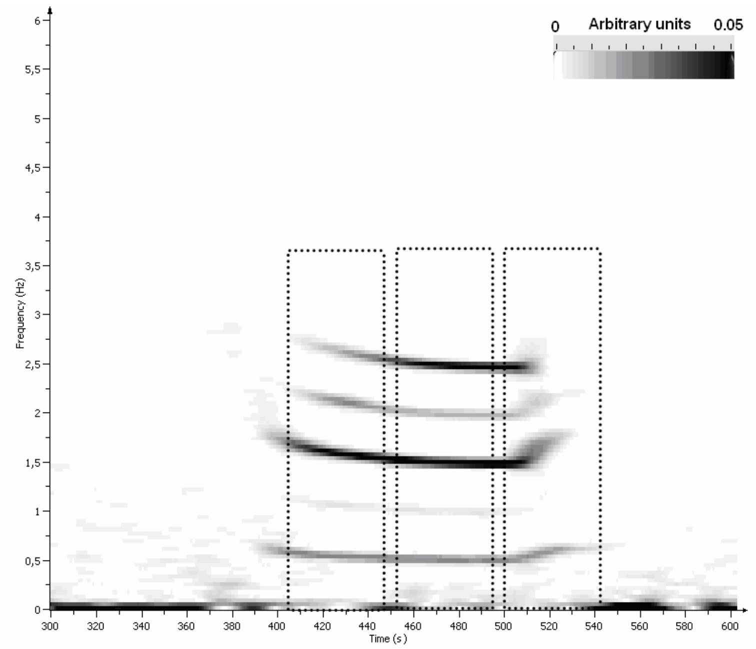


Figure 11: joint time-frequency analysis of the signal

4. Testing and monitoring of public utilities

4.1 Indiano's bridge

Indiano's bridge is a modern bridge crossing the Arno river that is now part of the national cultural heritage. It support all-day a heavy vehicular traffic and cannot be kept easily out of service for testing.

Indeed, a measurement campaign has been performed just exploiting the excitation due to the passage of vehicles

Figure 12 shows the position where was installed the equipment and the obtained radar image. By selecting a peak, the displacement can be plotted as in Figure 13

Figure 12: testing and radar image of the Indiano's bridge

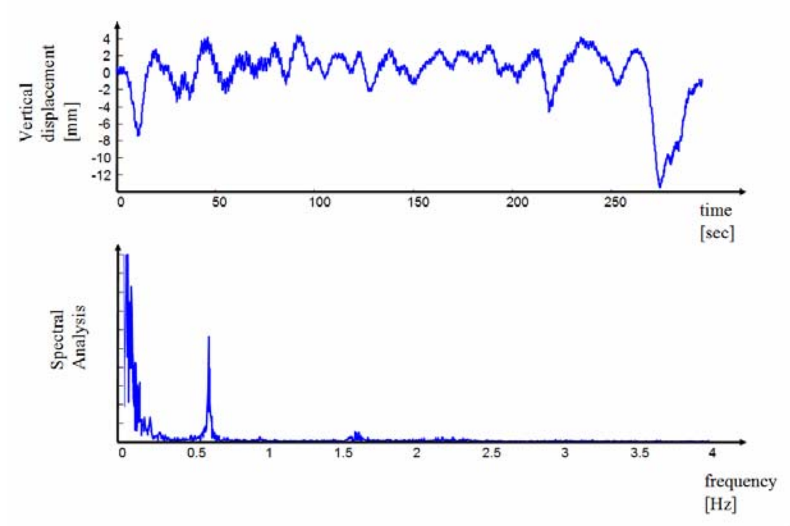


Figure 13: displacement of the peak labelled in Figure 12

4.2 Railway bridge testing

A measurement campaign was performed on a railway bridge going in service(9). It is a newly built twelve-arcades structure crossing the river Arno at Signa, near Florence, Italy. All the arcades have been object of static and dynamic tests, by using trucks and locomotives as forcing loads.
Static test has been performed by using as dead load three locked locomotives, weighting on the whole 400 tons: they arrived at the center of the arcade, stayed there for about 6 minutes, and after moved away. Figure 14 plots the displacement vs. time.

Figure 14: testing and radar image of the Indiano's bridge

4.3 Wind tower

The number of wind turbine towers installed worldwide is over several tens of thousands and is growing at rates exceeding 39% annually. All these structures are tested soon after installation, they need a periodical monitoring. The radar equipment has been successfully applied to monitor this kind of structures[11].

Figure 15: testing of a wind tower

By pointing along the tower as shown in Fig. 15 it is possible to obtain in real time the deformation of the tower due to the excitation of the wind. The natural frequency is easily obtained as in the cases above mentioned.
A very interesting possibility, it is to detect the effect of the aerodynamic load. Figure 16 (the first two images) shows the effect on two points of the structure when the blames are stopped. The upper point move of more than 10 cm that is the flexion due to the wind pressure. The lowest image in Figure 16 shows the envelope of the displacements along the height. At 35 m of height the maximum deflection is of 25 cm.

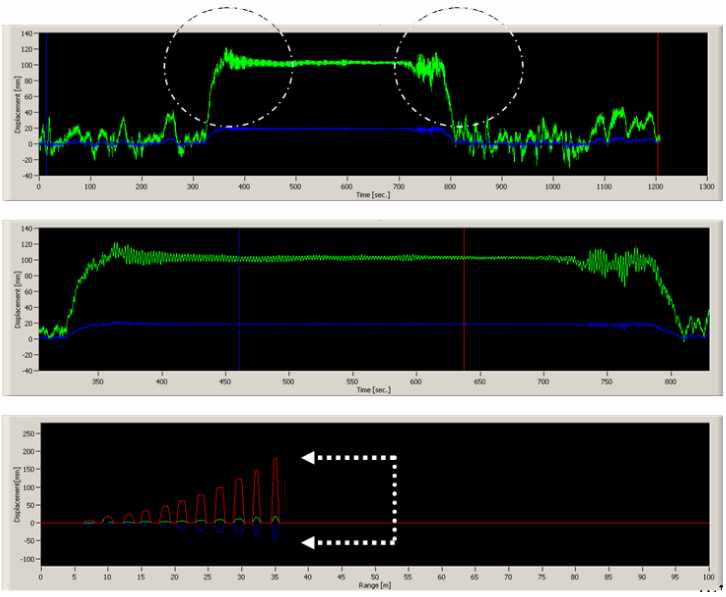


Figure 16: measured displacements of a wind turbine

5. Conclusions

Static and dynamic testing of large structures using interferometric radar appears a very attractive and promising tool for a number of reasons: it performs a remote measurement, not requiring contact with the structure; the measuring technique is rapid and simple; the same portable instrument performs both the static and dynamic tests, it can operate on in-service structures.

Nevertheless, when using radar interferometry, some word of caution is in order.

The position of the equipment with respect to the bridge is a key aspect for the success of this measurement technique. Extraneous targets (like trees, scaffolds..) interposed between the sensor and the structure can be prejudicial for the measurement. Simply speaking: "the equipment can detect only what it sees properly".

A bit of radar practice is needed in recognizing the echo response of the physical targets in the scenario.

It must be realized that the interferometric sensor detects only the component of the displacement along the radar line-of-sight direction.

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