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Dynamic damage identification of masonry lighthouse by radar interferometry technique

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***Abstract* – Our work addresses the capability of the radar interferometry technique to identify the dynamic behavior of an historical masonry lighthouse. To achieve this goal, we have performed a campaign of ambient vibration tests for characterizing the dynamic properties of the San Cataldo's lighthouse located in Bari using ground-based radar interferometry. Moreover, the experimental results were used to calibrate a numerical approach for the assessment of structural damage. Indeed, by analyzing five different damage scenarios, the ability of the radar interferometry technique to identify each damage was investigated.**

I. INTRODUCTION

The Structural Health Monitoring (SHM) plays a crucial role in the preservation and conservation of the architectural and archaeological heritage widespread in the Italian territory. Among the various experimental techniques aimed to dynamic identification of structure, Ambient Vibration Testing (AVT) is one of the most effective approaches to identify the dynamic properties of historical masonry construction, since it does not involve the use of external forces that could damage the structure. In some recent works [1], [2], AVT has also been considered in developing innovative and advanced structural health monitoring systems based on the IoT paradigm.

Traditionally, these tests are carried out using accelerometers, which provide accurate results that allow us to effectively monitor the damage in structures, including masonry constructions. Some disadvantages related to the use of these sensors, especially the need of full access to the structure for the installation of the sensors, have pushed scientific and industrial research to formulate alternative experimental approaches. Nowadays, the ground-based radar interferometry seems to be one of the most promising methods for the dynamic identification of constructions, overcoming some of the typical disadvantages of the accelerometric sensors. Indeed, the radar interferometry technique makes it possible to measure structural vibrations at a great distance, thus eliminating the need of conducting time-consuming operations, and especially the requirements of full access to the structure.

Several works have shown the effectiveness of the ground-based radar interferometry technique for identifying modal properties of structure and infrastructures, such as concrete and steel bridges, wind turbines, chimneys of industrial plants, antenna masts, lighting towers, culverts, buildings, etc. Moreover, some applications have concerned the dynamic identification of tensile forces in stay-cables [3] and tie-rods [4].

Several works [5]–[8] have also investigated the possibility of using the radar interferometry technique to carry out experimental tests on masonry constructions.

As for slender masonry structures (like towers, bell towers, lighthouse and minarets structures), one of the first applications concerned the use of the interferometric radar for measuring the vibration of the bell tower of Giotto (Italy) [9]. In this work, the vibration induced by bell ringing at different height of the bell tower was measured by an interferometric radar system. In [10] the dynamic monitoring of some masonry civic towers in Florence (Italy) was performed by using the radar interferometry technique. By comparing the radar results with those obtained from accelerometer tests, the authors confirmed the effectiveness of this application. In [11], AVT was carried out for monitoring the Leaning Tower of Pisa (Italy) by means of the interferometric radar. Here, the Authors have identified the first two natural frequencies of the tower, and have also estimated the associated mode shapes by making specific assumption about their direction.

In some works [12]–[13], the interferometric radar results obtained from ambient vibration tests on masonry bell towers were compared with those obtained from accelerometer measurements, showing that the radar is capable of measuring the first natural frequencies of the structure.

In our work, we have investigated the possibility of using the ground-based radar interferometry technique to perform ambient vibration tests on a historical masonry lighthouse located in Bari (Apulia region, Italy). Moreover, starting from the experimental results, we have developed an approach to verify the ability of the interferometric technique to evaluate five possible damage scenarios of the structure.

II. A CASE STUDY: SAN CATALDO'S LIGHTHOUSE IN BARI

The radar interferometry technique was employed to perform *in situ* ambient vibration tests on a historical masonry lighthouse located in Bari: the San Cataldo's lighthouse (Figure 1). The building dates to the nineteenth century and consists of a service structure with a main front of 24.00 meters and a lateral front of 12.25 meters, and the tower, which is about 61.00 meters high. The tower has a tapered shape and an octagonal plan with a diameter of approximately 8.80 m at the base and 5.00 m at the top. The thickness of the walls varies from 2.90 m at the base to 1.00 m at the top. Inside, the tower houses a helical staircase.

Figure 1 San Cataldo's lighthouse in Bari

The interferometric radar tests are carried out with an IBIS-FS system [7] consisting of a sensor module for generating, transmitting and receiving electromagnetic signals using different kind of antennas pair, and a PC for managing the tests and storing the signals (Figure 2).

Figure 2 The interferometric radar system

Two radar measurement have been performed from two different positions. In the first acquisition the angle of inclination of the radar sensor was equal to 35.1° (Figure 3), in the second it was equal to 35.8° (Figure 4). Both the measurement lasted 60 minutes. The signals were acquired with a sampling frequency of 200 Hz.

In order to remove the vibration of the IBIS sensor, a monoaxial piezoelectric accelerometer (PCB Piezotronics 393B05) was installed on the radar [7]. In this way it was possible to measure the vibration of the instrument, which was then subtracted from the vibration of the structure detected by the radar during the tests.

Figure 3 First radar acquisition position

Figure 4 Second radar acquisition position

III. DATA PROCESSING AND RESULTS

The data acquired through the radar interferometer were initially processed through the IBIS Data Viewer software. The IBIS-FS system provides only range resolution (it does not provide azimuth resolution) and discretize the scenario in resolution cells, called "Rangebins". Therefore, from the analysis of the Range profile, we have first selected the Rangebins corresponding to significative points of the lighthouse. The selected Rangebins are shown in Figure 5.

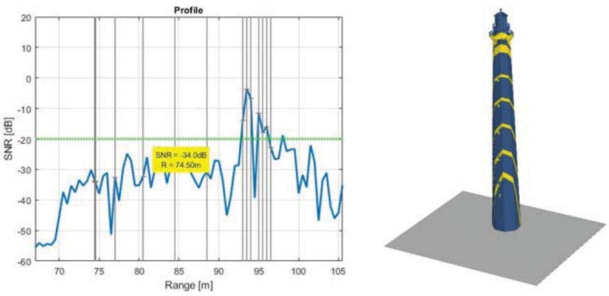

Figure 5 Range profile

The displacement time series extracted from the selected Rangebins were then processed through the ARTeMIS Modal software. By applying the Enhanced Frequency Domain Decomposition (EFDD) method to the signals obtained from the first acquisition, four frequencies equal to 1.064 Hz, 4.677 Hz, 7.135 Hz and 8.880 Hz were determined (Figure 6).

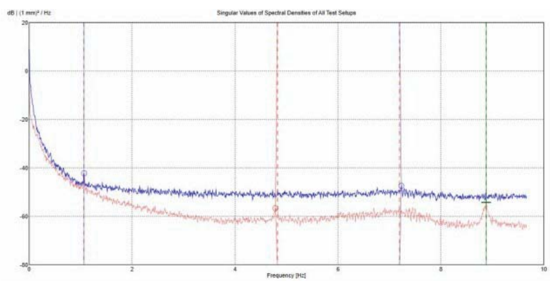

Figure 6 PSD functions of displacements detected from first position.

Similar results were obtained from the second acquisition. However, by comparing the spectra obtained from the interferometric measurements with those obtained from the accelerometer positioned on the IBIS sensor (Figure 7), it results that the frequencies corresponding to the values 7.135 Hz and 8.881 Hz were due to the vibration of the instrument; consequently, those values were discarded. As a result, the two main frequencies of the structure, corresponding to 1.064 Hz and 4.677 Hz, were identified.

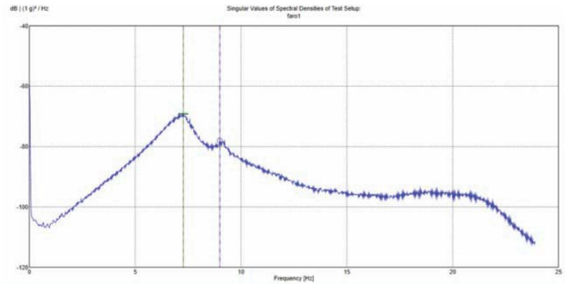

Figure 7 PSD functions of displacements detected from the piezoelectric accelerometer located on the interferometric sensor.

In the absence of a comparison with accelerometric test results, the validation of the experimental results was carried out by comparing the value of the first frequency experimentally obtained with theoretical values obtained from empirical formulas proposed in [14]. In particular, using the theoretical formulas related to the categories of structures "All types of slender structures" and "Masonry tower", we have obtained two estimations of the first natural frequency, i.e., 1.076 Hz and 1.056 Hz, respectively, which are very close to the value of the first frequency experimentally obtained.

III. DAMAGE IDENTIFICATION APPROACH

A numerical model of the undamaged structure was developed using the software *Straus7*. A simplified geometry of the structure was created, that is a truncated pyramid with an octagonal base of 49.59 m high. The helical staircase was modeled as a beam element connected by rigid link to the structure of the lighthouse. The structure was constrained at the base by means of interlocking constraints as the soil-structure interaction was considered not significant for the developed analysis. Starting from the initial values of Young's modulus of masonry obtained by previous tests with flat jacks, the mechanical properties of the masonry were iteratively calibrated by comparing the results of the frequencies numerically obtained with the experimental ones. In Figure 7 we show the modal shapes associated with the first four fundamental frequencies obtained with an average Young's modulus equal to 3300 MPa, a Poisson ratio of 0.2, and a material density of 1631.52 kg/m^3.

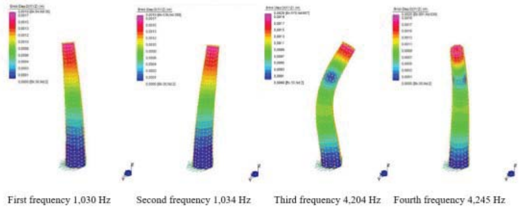

Figure 8 Numerical results: modal shapes and frequencies

Starting from the numerical model of the undamaged lighthouse, some models have been developed to simulate five possible damage scenarios of the structure. The damage was simulated by considering, in very limited areas, a decrease of the elastic modulus as a function of a parameter α. For each damage scenario, we analyzed which of the main four frequencies were most affected. The results obtained are shown in the following figures (Figures 9-12).

In Figure 9, we have a typical damage that occurs at the top of the lighthouse, due for example to lightning. We observe that the second and third frequencies are most influenced by this kind of damage with respect to the other frequencies.

Figure 9 Numerical results related to the damage scenario 1

Figure 10 and Figure 11 reproduce a damage which takes place at the base of the lighthouse. In both damage scenarios, all frequencies are sensitive to the damage. In the first case, the first and the second frequency are most influenced, while in the second case the first frequency is mainly affected.

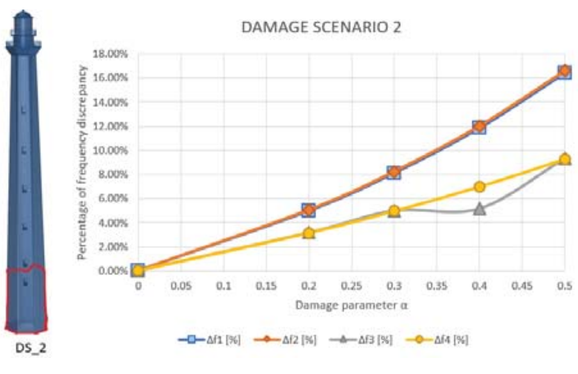

Figure 10 Numerical results related to the damage scenario 2

In Figure 12 the damage regards a central portion of the lighthouse. Here the second and the third frequency, respectively, are more sensitive to damage.

Finally, Figure 13 reproduce a damage localized to the top of the lighthouse, but of lesser extent than that of Figure 9. We observe results similar to those seen with regard to Figure 9.

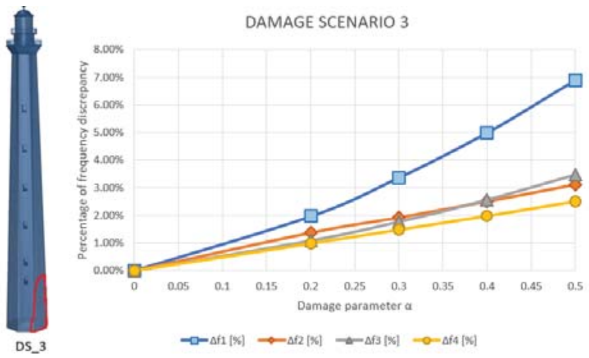

Figure 11 Numerical results related to the damage scenario 3

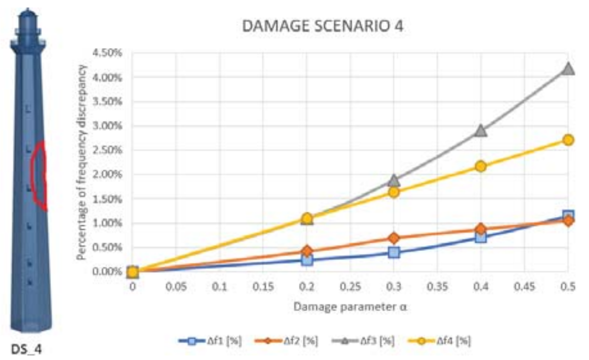

Figure 12 Numerical results related to the damage scenario 4

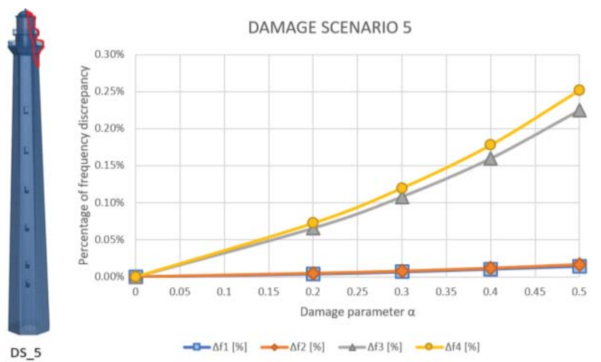

Figure 13 Numerical results related to the damage scenario 5

From the analysis of the damage scenarios, it is clear that either the first or the third frequency are always affected by the damage. These are also the only two frequencies measured by the interferometric technique during the two acquisition positions. Therefore, these results suggest that the radar interferometry technique can be potentially used for the dynamic identification of structural damage of slender masonry constructions, such as the lighthouse here investigated.

IV. CONCLUSIONS

In this paper *in situ* AVT were performed on a historical masonry lighthouse in order to characterize its dynamic properties. Using the ground-based radar interferometry technique we have identified the first main frequencies of the structures by only two radar acquisition positions. Moreover, starting from experimental results we have calibrated a numerical model of the masonry structure, which was used to develop five possible damage scenarios that can occur in a slender masonry structure like the lighthouse. From the analysis of the damage scenarios, it was observed that the frequencies identified from the two radar acquisitions also was the most sensitive frequencies in each damage scenario. This result shows that the radar interferometry is not only able to identify the first fundamental frequencies of a masonry structure, but also to monitor the health status of the structure (SHM) by detecting some possible damage scenarios.

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