ACTA IMEKO
ISSN: 2221-870X
September 2023, Volume 12, Number 3, 1 - 6

Dynamic damage characterization of slender masonry structures by radar interferometry: a case study

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ABSTRACT
The work shows an experimental and numerical investigation on the dynamic identification of damage in slender masonry structures using the innovative remote sensing technique of ground-based radar interferometry. The case study concerns San Cataldo's masonry lighthouse, which is located in Puglia (Italy). Here, we experimentally determine the natural frequencies of the lighthouse by carrying out Ambient Vibration Tests (AVT) using an interferometric radar system. Starting from the experimental results, we calibrate a numerical model of the structure and study the sensitivity of the first natural frequencies of the model to five possible damage scenarios involving different parts of the structure and different degrees of damage. Comparing numerical and experimental results, we show that the interferometric radar can be effectively applied to detect damage involving the lower part of the structure.

Section: RESEARCH PAPER

Keywords: structural health monitoring; ambient vibration testing; slender masonry structures; radar interferometry technique; damage characterization

Citation: Domenico Camassa, Anna Castellano, Mariateresa Chiapperino, Aguinaldo Fraddosio, Francesco Paparella, Mario Daniele Piccioni, Dynamic damage characterization of slender masonry structures by radar interferometry: a case study, Acta IMEKO, vol. 12, no. 3, article 5, September 2023, identifier: IMEKO-ACTA-12 (2023)-03-05

Section Editor: Leonardo Iannucci, Politecnico di Torino, Italy

Received January 14, 2023; **In final form** March 15, 2023; **Published** September 2023

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1. INTRODUCTION

In recent decades, the assessment of the structural health state has gained increasing importance especially in the planning of restoration and maintenance of historic masonry constructions [1]-[2].

The Structural Health Monitoring (SHM) consists of a set of experimental techniques, data acquisition methods and mechanical models that have the purpose of evaluating the state of health of a structure in a continuous way, even in operating conditions [3]-[5]. Traditional monitoring systems require the installation of an adequate number of accelerometric sensors on structures in order to identify structural parameters, global or local, useful for identifying potential damage [6]-[11]. Although the high reliability and accuracy of these traditional sensors, they also have a number of limitations related to the need to have direct contact with the structure as well as long installation times. Another disadvantage is due to the fact that the accelerometer are discrete measurement sensors, able to define the behaviour of the structure only in the points where they are installed; this can lead to a loss of information in the areas of the structure where these sensors are not present.

In the last decade there has been a growing development of innovative solutions for the expeditious identification of the dynamic properties of structures and infrastructures, and for the periodic monitoring of their state of conservation. Among the emerging technologies in this area, remote sensing systems have played a predominant role.

The ground-based radar interferometry (Figure 1) represents one of the remote sensing techniques that is proposed as a substitute for the methods used up to now for structural monitoring, as it is able to overcome the typical limits of accelerometric sensors [12]-[14].

The obvious advantages of this technique, such as the speed of installation of the instrumentation and data acquisition, and the high spatial and temporal resolution of sampling, have motivated the growing interest of the scientific community to verify the capabilities in the dynamic identification not only of steel and concrete structures, but also of masonry constructions.

The main works in the scientific literature concern the application for the identification of the modal properties of

Figure 1. The interferometric radar system [18].

concrete and steel bridges [15]-[16], wind turbines, chimneys of industrial plants, antenna masts, lighting towers, culverts, buildings, etc. Some works regard the dynamic identification of tensile forces in stay-cables [17] and tie-rods [18]. Instead, few works [19]–[23] have investigated the possibility of using the radar interferometry technique to identify the modal properties of masonry constructions.

The proposed work aims to evaluate the effectiveness of the interferometric radar technique for the dynamic damage identification of a slender masonry structure: the lighthouse of “Punta San Cataldo” located in Bari. In particular, Ambient Vibration Tests (AVT), according to the Operational Modal Analysis (OMA) technique [24]-[26], were performed since it does not involve the use of external forces that could damage the lighthouse structure. In some recent works [27]-[37], AVT has also been considered in developing innovative and advanced structural health monitoring systems based on the IoT paradigm.

The experimental results were first validated with some theoretical formulas useful for determining the first principal frequencies of slender structures, and then used to calibrate a numerical model of the lighthouse in the absence of damage.

Thus, different damage scenarios that can occur for slender masonry structures such as lighthouses and chimneys were numerically simulated, and the effectiveness of the radar interferometric technique in evaluating each single damage scenario was investigated.

1. DYNAMIC IDENTIFICATION OF MASONRY LIGHTHOUSE

1.1. Setup

The case study regards an historical masonry lighthouse located in Bari: the San Cataldo’s lighthouse (Figure 2). The structure was built on the Bari seafront between 1967 and 1969 and has the following geometrical features: 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 shows a tapered shape and has 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. Moreover, the tower encloses a helical staircase.

The setup for radar interferometric tests consists of the IBIS-FS system, which is equipped by a sensor module for generating, transmitting and receiving electromagnetic signals using different kind of antennas pair (Figure 2), and a PC for managing the tests and storing the signals.

Figure 2. San Cataldo’s lighthouse in Bari.

Since the radar interferometer also records the vibrations of the sensor module, during the dynamic identification tests of the structure, it has been installed a monoaxial piezoelectric accelerometer (PCB Piezotronics 393B05) on the sensor box. So, the vibrations of the instrument were subtracted from the vibrations of the structure detected by the radar during the tests.

The tests were then carried out by positioning the radar in two different stations. In the first station the angle of inclination of the radar sensor was equal to 35.1° (Figure 3,a), while in the second station it was equal to 35.8° (Figure 3,b). Both the measurement acquisitions lasted 60 minutes and the signals were acquired with a sampling frequency of 200 Hz.

1.2. Dynamic results

The data acquired in the two radar stations were first processed with the IBIS-Data Viewer software and subsequently by using the Artemis Modal software.

In particular, in each acquisition, the more significant range bins were selected (Figure 4).

Then, the signals extracted from the selected range bins were properly processed. In particular, the Artemis Modal software

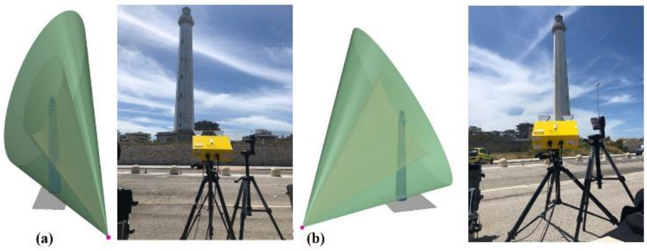

Figure 3. Radar acquisition stations.

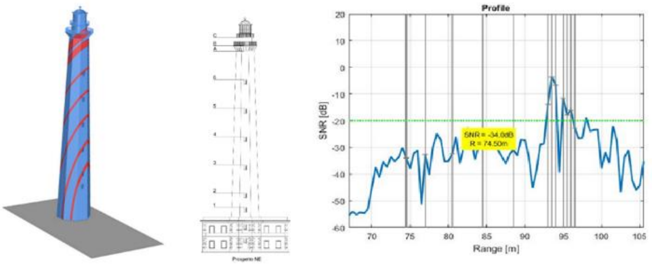

Figure 4. Range profile.

Table 1. Experimental frequencies.

Number	f_{IBIS} (Hz)	f_{acc} (Hz)
1	1.064	---
2	4.677	---
3	7.135	7.135
4	8.880	8.881

was used to identify natural frequencies from the signals. So, applying the Enhanced Frequency Domain Decomposition 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 measured. Similar results were obtained from the second acquisition. However, these frequencies could include those related to the vibration of the tripod on which the radar module is installed. So, by analyzing the signals recorded by the accelerometer that we have installed on the radar sensors for measuring its vibration, we noticed that the last two frequencies actually were the natural frequencies of the tripod. Therefore, we excluded those frequencies. As a result, the two identified natural frequencies of the lighthouse are those at about 1 Hz and 4.677 Hz (Table 1).

Since the results of accelerometric tests are not available, the results obtained from the interferometric tests have been validated by comparing the experimental value of the first frequency with theoretical values obtained from empirical formulas proposed in [38] with reference to the categories of structures “All types of slender structures” and “Masonry tower”. In these two cases, the values of the first main frequency were determined equal to 1.076 Hz and 1.056 Hz, respectively. These theoretical values are very close to the value of the first frequency experimentally obtained.

2. DYNAMIC DAMAGE IDENTIFICATION STRATEGY

2.1. Numerical model of the undamaged structure

The radar results were used for the calibration of a numerical model of the undamaged structure. The model was built by using the software *Straus7* and was useful for the development of the proposed approach for the dynamic identification of the damage. A simplified geometry of the lighthouse was generated. It consists in a truncated pyramid with an octagonal base of 49.59 m high. The model was constrained at the base by fixed constraints as the soil-structure interaction was considered not significant for the developed analysis. Moreover, the helical staircase was modeled as a beam element connected by rigid link to the structure.

Initially using the value of the Young’s modulus of masonry structure obtained from flat jacks tests that we have performed in a previous experimental campaign, the mechanical properties of the masonry were then calibrated by fitting the natural frequencies (Table 2).

As it can be seen, the fundamental frequency of the model is very similar to the experimental one. Furthermore, the second frequency that we have experimentally determined correspond to the third frequency of the structure.

Table 2. Numerical frequencies.

Number	f_{IBIS} (Hz)	f_{acc} (Hz)	D_{f} (%)
1	1.064	1.030	3.30
2	---	1.034	---
3	4.677	4.204	11.25
4	---	4.245	---

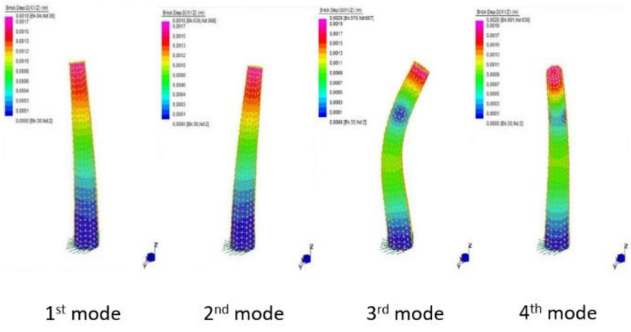

Figure 5. Numerical results: mode shapes and frequencies.

Figure 5 show the first four modal shapes and the related frequencies of the undamaged lighthouse obtained by the numerical model in the hypothesis of 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.

2.2. Damage scenarios

In order to evaluate the possibility of detecting the structural damage from changes in natural frequencies, we used the calibrated numerical model to study the sensitivity of the first four natural frequencies of the model to five possible damage scenarios. The damage was simulated by considering a decrease of the elastic modulus in limited areas of the structure:

$$E(\alpha) = (1 - \alpha)\, E_0\,, \tag{1}$$

where the scalar parameter $\alpha \in [0,1]$ measures the damage, E_0 is the Young’s modulus in the absence of damage, $E(\alpha)$ is the Young’s modulus in presence of the damage.

Figure 6 shows the five damage scenarios that can actually occur in a slender masonry structure.

For each damage scenario, the main four frequencies of the model were analysed.

The first damage scenario reproduces a damage that takes place at the base of the lighthouse (Figure 7). In the graphs, the damage parameter α is on the x-axis, and the percentage change of frequency is on the y-axis. These lines represent percentage changes of the first four frequencies of the model as function of the damage parameter.

As it can be seen, all the four frequencies are sensitive to the damage. In particular, the first and the second ones are the most affected. For example, a decrease of 50 % of the Young's

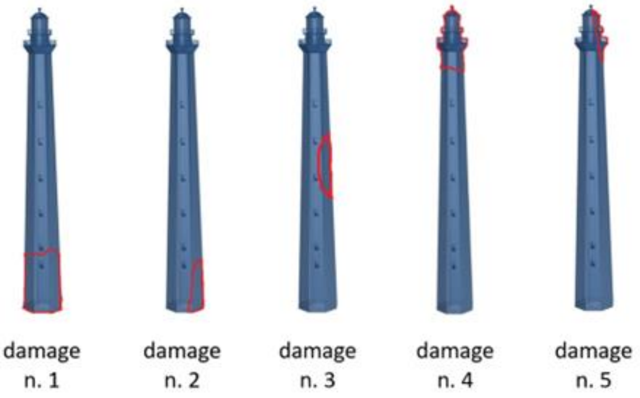

Figure 6. The five damage scenarios.

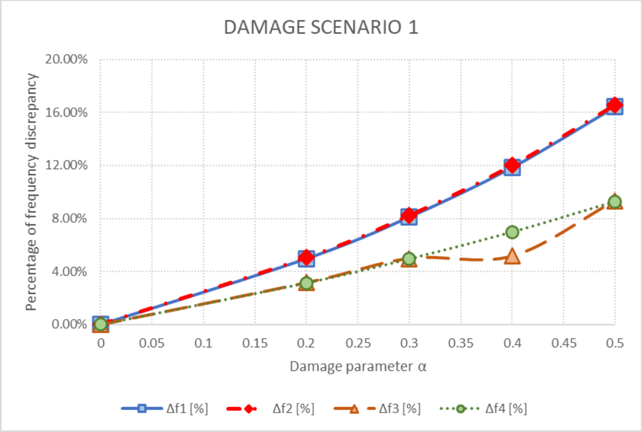

Figure 7. First damage scenario.

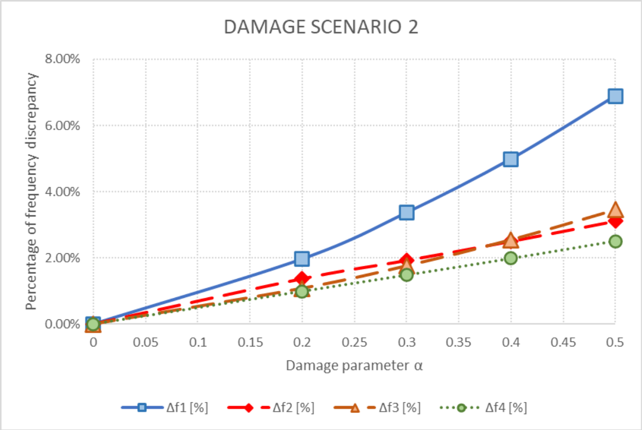

Figure 8. Second damage scenario.

modulus correspond to a 16 % of variation of the first and the second natural frequencies.

The second damage scenario (Figure 8) is similar to the first one, but the damaged area is more limited. Also in this case, the four frequencies are all sensitive to the damage, although less than the previous case. For example, a decrease of 50% of the Young's modulus correspond to a 7% of variation of the first natural frequency. Here, the first frequency is the most affected.

In the third scenario (Figure 9), the damage regards a central portion of the structure. Here, the third and the fourth frequencies are the most affected, while the first and the second ones are poorly affected. For example, a reduction of 50% of the Young's modulus in the red area correspond to a variation of just 1% of the first and second frequencies.

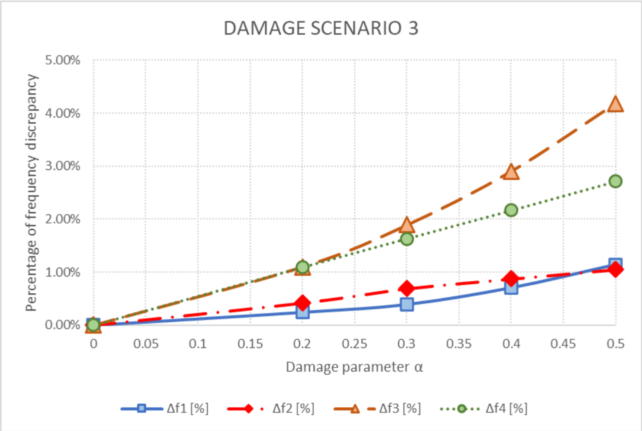

Figure 9. Third damage scenario.

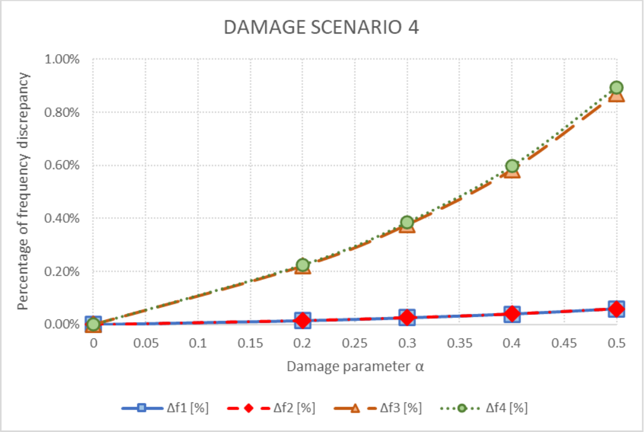

Figure 10. Fourth damage scenario.

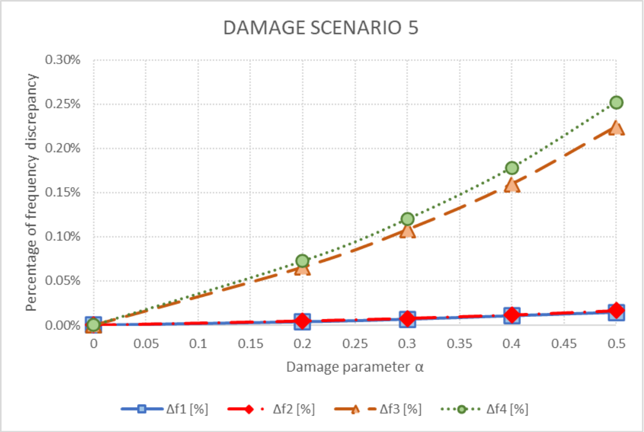

Figure 11. Fifth damage scenario.

The fourth scenario (Figure 10) reproduces a damage that is localized at the top of the lighthouse. In this case, all the four frequencies are poorly affected. Indeed, a variation of 0.9% of the third and the fourth frequencies occurs for a reduction of 50% of the elastic modulus. The first and the second frequencies are almost not affected at all. This can be justified by studying the deformation of a plane cantilever beam. It can be seen that the curvature of the first mode shape is very low at the top of the beam. Therefore, damage in this area poorly affect the first natural frequency.

The fifth scenario (Figure 11) is similar to the previous one but regards a more limited area. Also in this case, the frequencies are poorly affected by the damage.

2.3. Discussion

In the following discussion we consider only the first and the third natural frequencies of the structure since they are the only two frequencies obtained by the interferometric radar measurements. Table 3 summarizes the changes in the first frequency in relation to the damage parameter and the damage scenario, while Table 4 summarizes the results related to the third natural frequency.

In addition to structural damage, there are also other factors that may cause changes in natural frequencies, such as temperature changes, humidity, measurement errors, etc. In general, a threshold value for frequency changes is set to detect structural damage with confidence. If a frequency change

Table 3. Percentage changes of the first frequency as function of the damage parameter and the damage scenario.

α	damage scenario				
	1	2	3	4	5
0.2	4.98	1.97	0.24	0.01	0.00
0.3	8.12	3.37	0.39	0.03	0.01
0.4	11.86	4.99	0.71	0.04	0.01
0.5	16.42	6.89	1.15	0.06	0.01

Table 4. Percentage changes of the third frequency as function of the damage parameter and the damage scenario.

α	damage scenario				
	1	2	3	4	5
0.2	3.16	1.08	1.10	0.22	0.07
0.3	4.99	1.76	1.89	0.38	0.11
0.4	5.17	2.55	2.91	0.58	0.16
0.5	9.33	3.46	4.19	0.87	0.22

exceeds the threshold value, then it is assumed that the damage can be detected with confidence.

Here two different values of threshold were considered. First, a threshold of 2% was used. For this value, the fundamental frequency makes it possible to detect the damage scenarios 1 and 2, which involve damage at the bottom of the lighthouse; the third frequency allows us to also detect the damage scenario 3, which involve the middle part of the structure. Although the third frequency is capable of detecting more damage scenarios than the fundamental frequency, it should be noted that, for the second damage scenario, the fundamental frequency is more sensitive than the third one.

Let us now consider a threshold value of 5%, as suggested in a study of Salawu [39]. In this case, the fundamental frequency is still capable of detecting the damage scenarios 1 and 2, but the second damage scenario can be detected only if the damage parameter is greater than 0.4; the third frequency can only detect the damage scenario 1.

In conclusion, within a threshold value of 5% for frequency changes, the interferometric radar may allow us to detect the first two damage scenarios. It is possible to justify this result by observing that the first two scenarios involve damage at the base of the structure, which corresponds to the higher stress concentration in both the first and the third mode shapes of the lighthouse.

3. CONCLUSIONS

In this work, it was investigated the possibility of using the radar interferometry technique for characterizing structural damage of masonry slender structures by detecting changes in natural frequencies.

Starting from experimental results, a numerical model of the undamaged structure was calibrated. The model was used to simulate five possible damage scenarios that can occur in a slender masonry structure like the lighthouse, and to study the sensitivity of the detected natural frequencies to the simulated damage.

The results show that the radar interferometry technique can be effectively applied not only to identify the first natural frequencies of a structure, but also to monitor the health status of the structure (SHM) by detecting possible damage scenarios, especially those affecting the lower and the middle part of the lighthouse.

Future works will include considering the effect of environmental factors (temperature changes, humidity, etc.) on natural frequencies, and also taking into account changes in mode shapes to detect and characterize the damage.

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