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Modal testing of masonry constructions by ground-based radar interferometry for structural health monitoring: A mini review

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Modal testing is one of the most effective experimental techniques for the structural health monitoring of masonry constructions, as it provides useful information for the calibration of structural models and for the assessment of structural damage. However, the application of modal testing to masonry constructions is sometimes hindered by the complexity of the conventional experimental set-up, which is generally based on contact sensors. In order to overcome this issue, several researchers are exploring the application of the ground-based radar interferometry, which is an increasingly popular measurement technique for remotely monitoring displacement and vibration of structures. Given the recently increasing number of articles on this subject, here we propose a mini review on the most significant works dealing with the application of ground-based radar interferometry for modal testing of masonry constructions. In particular, we show the current state of the art and highlight the main research gaps with the purpose of assessing the effectiveness of ground-based radar interferometry for the structural health monitoring of these constructions. Our mini review is primarily aimed at engineers and scientists who already know about modal testing and radar interferometry technique and are interested in the specific application to masonry constructions.

KEYWORDS

radar interferometry, modal testing, masonry constructions, remote sensing, structural health monitoring, cultural heritage

1 Introduction

Historical masonry constructions represent the most widespread architectural and cultural heritage of our territory. Due to the high vulnerability to damage, masonry constructions must be preserved and safeguarded over time. Appropriate conservation and restoration interventions require suitable investigation procedures (Binda et al., 2000), which mainly involves non-destructive techniques (Carpinteri et al., 2007; Ramos et al., 2010a; Castellano et al., 2015; Castellano et al., 2016; Camassa et al., 2019; Camassa et al., 2020; Pallarés et al., 2021). Among them, modal testing has the very appealing feature of monitoring the global response of a structure. This experimental technique provides the modal properties of a structure (natural frequencies, mode shapes, modal damping ratios) by measuring and analyzing structural vibration due to the external load (Salawu and Williams, 1995; Peeters and Ventura, 2003; Ivorra and Pallarés, 2006; Ramos et al., 2010b; Bartoli et al., 2013).

Structural vibration is generally measured through contact sensors (e.g., accelerometers). Despite the high measurement accuracy of these sensors, their installation on the structure is time consuming and require the full access to the structure. These issues often hinder the

TABLE 1 Summary of the reviewed papers related to modal testing of masonry constructions by radar interferometry.

Author/s, Year	Structure	Dynamic excitation	Identification algorithm	Results
Pieraccini et al. (2005)	• Giotto's bell tower (Firenze, Italy)	• Bells ringing	• FFT	• Cadence of the tolling • Operating deflection shape
Pieraccini et al. (2007)	• Bell tower	• Bells ringing	• Joint time-frequency • transfer function (FFT) analysis	• 2 natural frequencies
Pieraccini et al. (2009)	• Giotto's bell tower (Firenze, Italy) • Arnolfo's tower clock (Firenze, Italy)	• Ambient loads • Bells ringing	• FFT	• 1 natural frequency (for both the bell towers)
Atzeni et al. (2010)	• Leaning tower of Pisa (Pisa, Italy)	• Ambient loads	• PP on PSD (for natural frequencies) • FDD (for mode shapes)	• 2 natural frequencies (along orthogonal directions) • 2 mode shapes (along orthogonal directions)
Fratini et al. (2011)	• Dome of the Baptistery of San Giovanni (Firenze, Italy)	• Ambient loads	• PP on PSD • joint time-frequency analysis	• 1 natural frequency
Gentile and Saisi (2012)	• Bell tower	• Ambient loads	• PP on PSD	• 2 natural frequencies
Calcina et al. (2013)	• Bell tower (damaged and inaccessible)	• Ambient loads	• FDD	• 1 natural frequency • 1 mode shape
Marchisio et al. (2014)	• Leaning Tower of Pisa (Pisa, Italy)	• Ambient loads • Movement of people	• PP on PSD (for natural frequencies) • FDD (for mode shapes)	• 1 natural frequency (in both loading conditions) • 1 mode shape (in both loading conditions)
Gentile and Saisi (2014)	• 2 bell towers	• Ambient loads	• PP on PSD	• 2 natural frequencies (for both the bell towers)
Pieraccini et al. (2014)	• Torre del Mangia (Siena, Italy)	• Ambient loads	• PP on PSD (for natural frequencies) • FDD (for mode shapes)	• 4 natural frequencies • 2 mode shapes
Saisi et al. (2016)	• Bell tower	• Ambient loads • Bells ringing	• FDD	• 1 natural frequency
Calcina et al. (2016)	• 2 almost twin bell towers	• Ambient loads	• PP on PSD	• 2 natural frequencies (for one of the two towers) • 5 natural frequencies (for the other one)
Pieraccini (2017)	• Several towers	• Ambient loads	• PP on PSD (for natural frequencies) • joint time-frequency analysis (for natural frequencies) • FDD (for mode shapes)	• 1–2 natural frequencies • 1–2 mode shapes
Pepi et al. (2017)	• Masonry arch bridge	• Ambient loads • Movement of people	• PP on PSD	• 2 natural frequencies (movement of people)
Castellano et al. (2018)	• Bell tower	• Ambient loads	• PP on PSD	• 2 natural frequencies
Castagnetti et al. (2019)	• Bell tower	• Ambient loads • Bells ringing	• PP on PSD	• 1 natural frequency
Pieraccini et al. (2019)	• Railway masonry arch bridge	• Ambient loads • Train passage	• PP on PSD (ambient loads) • FFT (train passage)	• 5 natural frequencies (ambient loads) • 4 natural frequencies (train passage)
Camassa et al. (2022)	• Masonry arch bridge	• Ambient loads	• FDD	• 2 natural frequencies
Castellano et al. (2022)	• Bell tower	• Ambient loads	• SSI	• 1 natural frequency • 1 mode shape

application of modal testing on masonry constructions and encourage the development of contactless sensing techniques. A promising and increasingly popular technique is the ground-based radar interferometry, or more briefly radar interferometry.

Radar interferometry exploits phase information of back-reflected microwave signals for detecting small displacement and vibration of structures at great distance. Its working principles have been thoroughly described in several works (Gocał et al., 2013;

Pieraccini, 2013; Pieraccini and Miccinesi, 2019). Radar interferometry stems from space technology, which encouraged the development of portable sensors for remotely monitoring civil structures. After pioneering works (Tarchi et al., 1997; 1999; Farrar et al., 1999; Pieraccini et al., 2000; 2003), commercial systems have been properly designed for static and dynamic testing of structures (Gentile and Bernardini, 2010; Diaferio et al., 2017). The main applications concern bridges, towers, wind turbines, dams, and buildings. Compared with accelerometers, the interferometric radar is quick and easy to install and requires no access to the structure. However, it still shows some drawbacks mainly related to atmospheric influence, presence of clutters, phase jumps, broadband noise, and projection of displacement along the line-of-sight directions (Michel and Keller, 2021).

Some researchers have explored the possibility of using interferometric radar systems for monitoring the dynamic behavior of masonry constructions. The main applications concern modal testing of masonry towers and bridges. Furthermore, a recent promising application concerns the dynamic identification of tensile force in tie rods (Gioffré et al., 2017; Camassa et al., 2021).

Here we discuss some meaningful works studying the employment of the radar interferometry technique for modal testing of masonry constructions. In particular, we explore the capability of estimating natural frequencies and mode shapes highlighting the promising effectiveness for Structural Health Monitoring (SHM) of masonry constructions and the main experimental and theoretical issues, also outlining possible research directions to enhance this application.

2 Identification of natural frequencies

In SHM of masonry constructions, the estimation of natural frequencies is of great importance both for the calibration of structural models and for the damage assessment. Natural frequencies are global properties of a structure that, in principle, do not depend on the measured point (except for nodal points), but only on the measurement accuracy. The interferometric radar is a device that could provide a good accuracy of displacement determination without the distinct location of the observed point (Gocał et al., 2013); consequently, it is particularly suitable for identifying natural frequencies of structures.

Several researchers have explored the capability of identifying natural frequencies of masonry towers (i.e., bell towers and civic towers) and masonry bridges by radar interferometry. In (Fratini et al., 2011) the natural frequencies of the dome of the Baptistery of San Giovanni (Firenze, Italy) were characterized. As for towers, the estimation of natural frequencies has proved to be as accurate as conventional accelerometers; nevertheless, a slight frequency shift has been observed (Castagnetti et al., 2019). As shown in Table 1, the frequencies associated with the first two bending modes (along orthogonal directions) are generally detected. Five frequencies were only estimated in (Calcina et al., 2016). As for bridges, in (Pieraccini et al., 2019) five natural frequencies of a very slender bridge were determined. To our knowledge, there are no articles in the literature on the topic that demonstrate the possibility of estimating higher frequencies.

The reliability of frequency identification primarily depends on the Signal-to-Noise Ratio (SNR) of the acquired displacement signals, which is related to both the measurement accuracy of the interferometric radar and the magnitude of the radar line-of-sight component of displacements of the observed point. Furthermore, the identification algorithm may play a fundamental role in the estimation of natural frequencies. Here, we discuss some fundamental key concepts on these aspects focusing on the dynamic excitation and the identification algorithm.

The accuracy of the interferometric radar mainly depends on the SNR of the echoes received by the surveyed targets (Thermal SNR). The higher is the Thermal SNR, the better is the measurement accuracy. Masonry constructions, however, poorly reflect electromagnetic waves due to the low reflectivity and the limited presence of "corner zones" (Gentile and Saisi, 2012; 2014). To improve the Thermal SNR, short-range measurements should be preferred (Pieraccini et al., 2009). Another possible strategy concerns the installation of corner reflectors on the structure (Pepi et al., 2017). However, this solution requires the access to the structure and reduces the very appealing feature of contactless monitoring of radar interferometry.

The magnitude of the displacement of an observed point could be increased either by properly setting the geometry of acquisition or enhancing the dynamic excitation. The relation between the geometry of acquisition and the magnitude of the line-of-sight displacement can be found by simple projection operations (Michel and Keller, 2021). The discussion about dynamic excitation requires deeper considerations.

2.1 Dynamic excitation

Regarding to the dynamic excitation of masonry constructions, which generally have a considerable historical and artistic value, Operational Modal Analysis (OMA), which only involves ambient loads (wind, vehicular and pedestrian traffic), is considered the most suitable modal testing technique since it does not cause any risk of damage. Several works exploit ambient loads for modal testing by radar interferometry on towers (Atzeni et al., 2010) and bridges (Camassa et al., 2022). Anyway, depending on the mass and stiffness of the structure, natural excitations may induce very low structural vibration, which results in radar signals with low SNR. Here artificial loads could be used. The main applications in the literature concern "random" impulsive and steady-state loads generated by the movement of people or the operation of the monitored structure (bells ringing for bell towers, train passage for railway bridges). Invasive artificial devices (vibrodynes, shakers, etc.) for generating structural vibrations are generally not used on masonry constructions because they may cause damage, especially on already damaged constructions.

Forced vibration induced by coordinate movement of people has been shown to effectively improve the SNR of radar signals. In (Marchisio et al., 2014), a good correspondence between the natural frequencies of the Leaning Tower of Pisa (Italy) estimated in ambient and forced loading conditions was found; furthermore, radar signals measured under artificial loads turned out to be more regular and smoother, and the maximum amplitude of vibration was up to thirty times greater than in ambient conditions. Movement of people was used as source of excitation also on a historic single-span arch bridge (Pepi et al., 2017). Ambient vibration test did not provide any significant result due to the very low level of vibration; quite the opposite, two natural frequencies of the bridge were estimated from forced vibration.

The bells ringing in masonry towers has proved to be effective to enhance the SNR of the measured signals. Some authors show that the dynamic response associated to the swinging of bells was four times larger than under ambient loads (Saisi et al., 2016). As for railway masonry bridges, an effective artificial dynamic load concerns the passage of a train (Pieraccini et al., 2019).

The above-mentioned artificial loads are able to induce larger vibration than ambient loads and, consequently, to increase the SNR of displacement signals acquired by the interferometric radar. Hence, the use of these solicitations is generally encouraged. However, in our opinion, some critical issues, often ignored, should be considered.

Coordinate movement of people may violate the assumptions of OMA methods. Movement should be nearly random and non-stationary; otherwise, the cadence of movement may arise in the spectra of the measured displacements and may be mixed up with structural frequencies. The bells ringing is a periodic excitation, with a spectrum quite different to broadband white noise (assumed in OMA methods). Consequently, some natural frequencies could not be excited enough to be detected in the spectra of the measured displacements; furthermore, the frequency of the bells oscillation can appear in the spectra, as in (Pieraccini et al., 2005; 2009), and may be misinterpreted as a natural frequency of the tower. To avoid the latter problem, further studies could investigate strategies to distinguish the frequency of the bells oscillation from the structural ones. Possible solutions may include the application of harmonic detection algorithms. Alternatively, only the free decay of the structural vibration induced by the bells may be monitored. Regarding the passage of trains on railway masonry bridges, it should be considered that the train has a considerable mass with the respect to the mass of the structure. Accordingly, as shown in (Pieraccini et al., 2019), a frequency drop should be expected.

Finally, when artificial loads are used to obtain a reliable estimation of natural frequencies, the non-linear behavior of masonry constructions should be also considered. Masonry constructions generally exhibit, even in the range of small strains, amplitude dependency effects, which cause frequency drops when the amplitude of vibration increases (Michel et al., 2011; Gentile and Saisi, 2013; Martakis et al., 2021; 2022). Information about frequency drops is of utmost importance for the structural monitoring and the early warning of damage (Gentile and Saisi, 2013). However, to our knowledge, a frequency drop has been detected by interferometric radar surveys only in (Saisi et al., 2016).

2.2 Identification methods

Although artificial loads make it possible to increase the SNR of the acquired signals, in many cases pure ambient loads are only available. For instance, structures that are not accessible and have no internal sources of vibration (bells, moving loads, etc.) can be only excited by wind and vehicular and pedestrian traffic in the surrounding area. In such situations, the application of appropriate signal processing and identification techniques may play a major role.

The identification procedures applied in the literature mainly concern methods in the frequency domain. In the first applications (Pieraccini et al., 2009), natural frequencies of masonry towers have been estimated from the Discrete Fourier Transform (DFT) of

acquired signals calculated by using the Fast Fourier Transform (FFT) algorithm. Ambient vibrations, however, are generally considered as random processes. As done in subsequent works, e.g., in (Atzeni et al., 2010), more advanced analysis of ambient vibration should be based on the application of suitable OMA methods, which generally require either the calculation of Power Spectral Density (PSD) functions in the frequency domain or Correlation Functions (CF) in the time domain.

Several authors have applied the Peak Picking (PP) method and the Frequency Domain Decomposition (FDD) method (Table 1), which are both based on the PSD functions. Due to the low SNR of radar signals acquired in low ambient vibration, the estimation of PSD should be based on methods capable of reducing noise in signals, such as the Welch's method. Furthermore, identification methods capable of rejecting noise (e.g., the FDD method) should be preferred. Very few studies have explored the application of methods in the time domain (Castellano et al., 2022) or in the joint time-frequency domain (Pieraccini et al., 2007; Fratini et al., 2011; Pieraccini, 2017).

It should be pointed out that, in the literature reviewed, well-established identification methods are just applied to radar signals. To improve the estimation of natural frequencies, further research should deeply address the application of more advanced methods (in any domain) by taking into account both the main features of radar signals and the mechanical behavior of masonry structures (e.g., the amplitude dependency effects). In particular, the application of robust methods capable of handling signals with low SNR measured from non-linear structures, such as the CoS-SSI (Liu et al., 2019) method, should be explored. Furthermore, comparative studies should be conducted by applying different dynamic identification methods on the same case study.

3 Reconstruction of mode shapes

Contrary to natural frequencies, a full reconstruction of mode shapes of masonry constructions requires information about both the position of the measured points and the measurement of the whole three-dimensional displacement vector of the observed points. The interferometric radar does not provide the exact position of the observed points nor the component of displacement orthogonal to the line-of-sight direction. Therefore, radar interferometry has inherent limitations in determining three-dimensional displacement vectors and full three-dimensional mode shapes of masonry structures. Nevertheless, information about mode shapes is of utmost importance both for the calibration of structural models and the identification of damage.

A first study for assessing the operating deflection shape of a masonry tower under the oscillation of its own bells is shown in (Pieraccini et al., 2005). The application of a more standard approach for identifying the mode shapes of the Leaning Tower of Pisa was explored in (Atzeni et al., 2010). The authors were able to identify two closely spaced bending modes in the orthogonal planes of the tower by applying the FDD method.

Since the interferometric radar only provide the line-of-sight displacement of a target, these studies are based on kinematic assumptions about the possible displacements of the monitored structure. Without such assumptions, only the projection of mode shapes along the line-of-sight directions can be achieved. However,
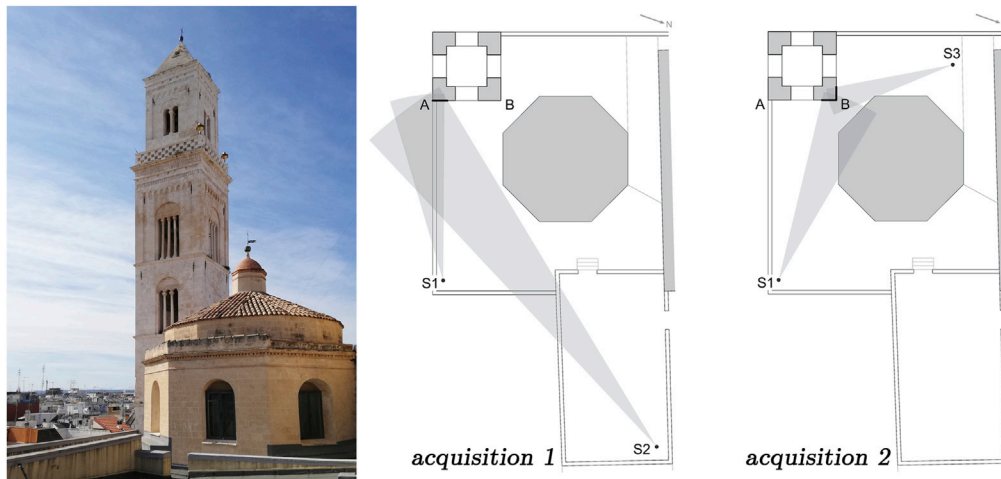
FIGURE 1
Different acquisitions that should be carried out with multiple interferometric radar systems to reconstruct full three-dimensional mode shapes of masonry constructions (S1, S2, and S3 represent the radar positions; the gray triangles represent the cone of view of the interferometric radar systems) (Castellano et al., 2022).

kinematic assumptions can only be applied to few types of constructions because, in general, the effective motion of a structure is unknown.

Some authors have proposed a number of solutions for reconstructing the whole displacement vector of a target. Except for a method able to detect both vertical and torsional movements of the sections of a bridge using an interferometric radar (Dei et al., 2009), other solutions are all based on the use of multiple interferometric radar sensors or bistatic radar systems (Michelini and Coppi, 2017; Monti-Guarnieri et al., 2018; Miccinesi et al., 2021; Michel and Keller, 2021; Olaszek et al., 2021).

The capability of estimating the displacement vector, however, does not directly imply the ability to reconstruct full three-dimensional mode shapes of large and complex masonry structures. In fact, it would be necessary to measure the vibration of the structure with multiple interferometric radar sensors from different points of view and, consequently, in different acquisitions (Figure 1). By applying OMA methods, it is possible to obtain partial three-dimensional mode shapes from each acquisition (i.e., mode shapes related to the degrees of freedom of the structure that are monitored in that acquisition), as shown in (Castellano et al., 2022). However, since OMA methods provide unscaled mode shapes (Rainieri and Fabbrocino, 2014), partial mode shapes estimated in different acquisition cannot be assembled in full mode shapes of the structure. This is a major limit of the use of radar interferometry for dynamic testing of masonry constructions. Further research to develop *ad hoc* methods for reconstructing mode shapes of masonry structures could lead to a great improvement in this application.

4 Discussion and future perspectives

Starting from the previous literature review, here we evaluate the advantages that radar interferometry can bring to the SHM of masonry constructions. We discuss the possibility of using modal properties estimated from interferometric radar measurements for the calibration of structural models (model updating) and the structural assessment.

Regarding the estimation of modal properties, the interferometric radar measurements make it possible to estimate the natural frequencies of the first bending modes and the projection of mode shapes along the line-of-sight directions. In general, neither higher natural frequencies nor full three-dimensional mode shapes can be obtained. The estimation of modal damping ratios is not explored in the literature, albeit information about the energy dissipation could be useful for damage detection (Ivorra et al., 2020).

In model updating, uncertain mechanical parameters are generally identified by minimizing the difference between theoretical and experimental modal behavior. A good updating may be obtained by just considering lower natural frequencies (Calcina et al., 2016; Castellano et al., 2018). More accurate results could be achieved by also considering mode shapes (Gentile and Saisi, 2007), which however cannot be completely estimated by radar interferometry.

As for structural assessment, it should be firstly noticed that, in general, structural damage is a local phenomenon. Therefore, the most useful modal properties for damage characterization are higher frequencies and mode shapes since they contain local information (Doebling et al., 1998; Fan and Qiao, 2011). Quite the opposite, lower frequencies are not very sensitive to localized damage because they are global properties of structures. Nevertheless, information about the fundamental frequency can still be used to detect damage that affects the whole structure, such as damage caused by seismic events (Calcina et al., 2013) or by foundation settlements (Castellano et al., 2021).

Finally, these considerations suggest that the interferometric radar can be effectively used to perform prompt dynamic tests on masonry constructions, especially in emergency conditions such as controls after seismic events (Saisi et al., 2016; Saisi and Gentile, 2020). In this vein, expeditious and no-contact approaches, as proposed in (Pieraccini et al., 2014), can provide pre-diagnostic information that may suggest deeper investigation with conventional contact sensors. Nevertheless, it emerged that, to date, the interferometric radar does not provide enough information to perform comprehensive structural monitoring of masonry constructions.

To enhance this application, in our opinion, future studies should be oriented toward two possible directions. One research line should be aimed at overcoming the limitations that emerged from this mini review, with a special focus on the identification of higher frequencies and the reconstruction of full mode shapes. Another research direction could involve the integration of radar interferometry with both Internet of Things (IoT) devices and satellite InSAR data (Selvakumaran et al., 2020; Scuro et al., 2021).

Author contributions

All authors contributed to the conception and intellectual framing of the review, and prepared the literature review and the first draft of the manuscript. All authors read and approved the submitted version.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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