Radar interferometry as a tool for structural health monitoring: current situation and perspectives of the technique for the next decade

G. Luzi, M. Crosetto
Centre Tecnològic de Telecomunicacions de Catalunya, Av. Gauss, 7, E-08860 Castelldefels (BCN), Spain
C. Gentile
Politecnico di Milano – Dept. of Arch., Built environment and Constr. Engineering. 20133 Milan, Italy

ABSTRACT: The development of interferometric radar sensors for the application to Civil Engineering structures took place in the last fifteen years, and the effectiveness of this technique has been demonstrated in different case studies. In this paper, after a brief introduction dedicated to the working principle, the main characteristics of the currently available sensors are summarized and the results of two tests are used to demonstrate how the main technical features of the radar sensor are linked to the final performances of the measurement in terms of spatial and temporal resolution. Furthermore, the potential improvements achievable using an updated technology nowadays available off-the-shelf are discussed as well. Some comments are also dedicated to the few advanced sensors recently described in literature, their potentials and limits. The overall analysis is carried out with the goal of evaluating the limits and advantages of this technique from the view point of the user communities.

1 INTRODUCTION

The development of Interferometric radar sensors for the monitoring of Civil Engineering structures dates back to the nineties. The effectiveness of the working principle has been demonstrated and specific equipment, including the basic processing and analysing tools, are nowadays available in the market. Different case studies on measuring the vibration characteristics of civil structures have been presented, and published papers are available in international journals from both radar and SHM communities.

To the authors' knowledge, the first use of an interferometric radar to measure the dynamic response of a structure dates back to 1999 (Farrar et al. 1999), when off-the-shelf electronic and microwave components measured the displacement response of target surfaces belonging to a bridge during forced vibration tests. In the following years, various experiments were carried out developing an apparatus initially not user friendly and based on costly and bulky microwave laboratory hardware (e.g. Pieraccini et al. 2000-2003). Later on, papers dealing with ambient vibration testing of structures using specific radar systems, devoted to this application, were published about bridges (Gentile & Bernardini 2008, Stabile et al. 2013), cables (Gentile and Ubertini, 2012), wind turbines (Pieraccini et al., 2008), historical towers (Atzeni et al. 210), tall towers (Luzi et al. 2013), chimneys (Rodelsberg et al. 2010) and buildings (Negulescu et al. 2013).

Radar interferometry demonstrated to provide displacement samples of any structure with submillimetre accuracy and from large ranges, with the limitation, due to the nature of the method, that only the component along the line of sight (LOS) of the radar can be measured.

Recently some papers tried to propose advanced sensors, taking profit from the present on the shelf microwave sensors, aiming not only at improving performances and capabilities of interferometric radar but also at proposing instrumentation with reduced costs. Currently no novel system has been definitely commercialized, and expected improvements have been only achieved in demonstration or trivial examples and not in real cases.

In this paper, the authors summarize the main technical features of the available radar sensors, how they are linked to the final performances of the measurement in terms of spatial and temporal resolution, and discuss the possible improvements achievable using an updated technology. Based on the state of the art, a crucial aspect for the design of an "optimal" new sensor stems from the different experimental conditions, i.e. the range, the size and characteristics of Civil Engineering structures, which strongly affects the measurement requirements. For this reason the development of advanced systems able to provide an optimum configuration of the proposed technology demands a strong interaction with the user communities.

2 THE TECHNIQUE AND THE INSTRUMENT

2.1 *The link between Microwaves and vibrations*

A radar uses the time elapsed between the transmitting and the receiving of an electromagnetic waveform to locate targets included in the illuminated area, and reflecting the radiation with sufficient strength to provide a sufficient signal to noise ratio. The output from the radar survey is a 1D range profile, the *range profile*, where different peaks correspond to contributions coming from targets located at different distances. When different targets are present, the radar is able to provide their displacement history using specific waveforms sweeping a finite band composed of different frequencies, B. Usually radar based on Frequency Modulated Continuous Wave (FMCW) or Step Frequency Continuous Wave (SFCW) instead of the standard pulse radio radar are used to assure coherent signals (Skolnik, 1990) and a capability of a sub-meter range resolution.

If the radar is coherent, also a phase value can be associated to the response of each target, and the minimum measurable displacement is of the order of small fractions of the transmitted wavelength. The range resolution ΔR, i.e. the minimum distance between two targets along the LOS at which they can still be detected individually is related to the swept band, B, according to the following equation:

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

Also the characteristics of the used antennas determine the elementary sampling volume of a radar measurement, usually called *radar bin.* Equation (2) states the relationship between the antenna size, D, and its field of view (FOV).

$$FOV = \frac{\lambda}{2D} \tag{2}$$

The use of an interferometric radar to detect the vibration of an object is based on the capability of a coherent radar working at microwave frequency, to measure variations in time of the differential phase of the received echo with respect to the transmitted signal. Remembering that the wavelength in vacuum, λ, and the central frequency, f, of the swept band are related by equation (3):

$$\lambda = \frac{c}{f} \tag{3}$$

a higher operating frequency means in general a higher sensitivity to displacement variation.

Considering that presently available apparatus uses a wavelength of the order of two centimeters, we can appreciate variations down to tens of microns. The vibration is seen by the radar as a range variation between the radar and the vibrating objects: in Figure 1 a simple scheme is depicted in the case where a single target is monitored. In this case the simple relationship between the measured differential phase and the displacement occurred along the LOS is expressed by the following equation (4).

$$d = \frac{\lambda}{4\pi}\Delta\varphi \tag{4}$$

The achievable accuracy is mainly determined by the signal to noise ratio of the acquisition which, in turn, depends on the intensity of the reflected signal. According to the radar equation (Skolnik, 1990), the intensity of the received radar signal, is affected by the radar reflecting properties of a target, the transmitted power, the distance, geometric factors (shape and orientation) and finally the dielectric characteristics of the target: a discussion about some of these issues can be found for example in Luzi et al. (2012), Coppi et al. (2010) and Cunlong et al. (2014).

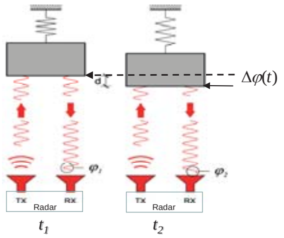

Figure 1: a scheme explaining the functioning principle of the radar Interferometry for vibration measurement. The target moves along the radar LOS inducing a variation in time of the measured interferometric phase.

In a more general case interferometric radar can provide sample of displacement time series following the procedure depicted in figure 2.

2.2 *The data processing*

The acquired radar signal processing can be divided into two separate subsequent steps: the first is aimed at retrieving the displacement samples from the received signal, and the second is dedicated to the interpretation of the entire measurement and the data analysis after associating the "good" radar bins to part of the vibrating scenario.

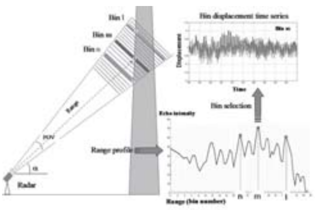

Figure 2. Scheme of an interferometric radar measurement: Acquisition of a range profile (left). Selection of the radar bin (right-down). Retrieval of displacement time history (right-up).

The first procedures are based on the use of radar processing tools like Fourier Transform and windowing, aiming at providing displacement histories for different parts of the monitored structure. The second step aims at the presentation of an operational product as a spatial modal description to support the dynamical test interpretation; standard tools of spectral analysis, as the auto-spectral densities (ASD) and specific algorithms dedicated to the modal analysis are used. The main vibration frequencies are determined analyzing its power spectral density, and usually for extracting the modal parameters from ambient vibration data different techniques are used: the Frequency Domain Decomposition (FDD) (e.g. see Brincker et al. 2000) and the Stochastic Subspace Identification (SSI) (Van Overschee and De Moor, 1996), as implemented for example in the commercial software ARTeMIS (SVS ARTeMIS Extractor, 2011). Despite the fundamental importance of the processing, which demands specific analysis tools, in this paper we do not deal with this topic, dedicating our considerations only to the pure instrumental and technical issues.

2.3 *The radar characteristics and the measurement performances*

On the bases of the fundamental equations recalled in the previous paragraph, the main radar characteristics affecting its performances when used as a displacement gauge can be here resumed as: working frequency, radiofrequency band and, of main concern from a marketing point of view, the problem of electromagnetic spectrum allocation and the maximum emitted power, regulated by governments in most countries. An example of a commercial systems available from the market is the Ibis-S manufactured by the IDS company, which operates at Ku band (17 GHz), i.e. with a wavelength lower than 2 centimeters and with a maximum band of 300 MHz (in Europe). The system is also prepared to allow the use of different antennas too, to better adapt the measuring condition to different geometries. A summary of its main characteristics are reported in Table 1.

The system was born almost ten years ago representing a fine trade-off among the discussed issues. In the last years the costs of microwave technology drastically lowered and the performances of the on-the shelf devices have strongly improved. This fact and the proposal of novel prototypes presently issued in literature (see for example: Cunlong et al. 2014, Grazzini et al. 2009 and Papi et al. 2014) and deserve an analysis about the effectiveness of improved radar interferometer sensors for civil structure vibration monitoring. The first step of this analysis starts from the characteristics of the present systems to be improved on the bases of some results obtained from literature.

Table 1. Main characteristics of the Ibis-S

Parameter	Value
Operating frequency	17.2 GHz (Ku band)
Maximum operational distance *	100 m
Range resolution	0.5 m
Nominal Displacement sensitivity	0.01 mm
Weight of the whole system	12 kg
Battery Autonomy	5 hours

* @ 40 Hz sampling frequency

3 TWO EXAMPLES

To show the importance of improving some the performances of the presently available apparatus, we exemplify through two case studies. In the first case rises the evidence of refining the range resolution to obtain an exhaustive monitoring of some structures, improving the monitoring of some suspended cables of a cable-suspended bridge. In the second case, focused on the monitoring of an urban building, where the displacements of the monitored structure are of the same order of the system accuracy, the analysis suggests improving the sensitivity and accuracy.

Here below we only recall specific issues: for an exhaustive description of the two studies we refer the readers to the original paper.

3.1 *The suspended cables of a bridge*

In Gentile et al. (2014) is described an example of the monitoring of a cable-suspended bridge carried out using an interferometric radar, aimed at an ambient vibration test. The investigated bridge crosses the Ebro River at Amposta, Spain. It consists of a main span of 134.0 m and two side-spans of 46.90 m each. The bridge was originally designed in 1913, destroyed in 1938, during the Civil War, and rebuilt in 1941 according to the original design. Subsequently, the bridge underwent two important strengthening interventions, in 1972 and 2007. The main span is supported by inclined stay cables and two series of 8 suspension cables. The Amposta bridge and [to be completed]

The dynamic tests were performed in operational conditions, with the sensor being placed in two different positions that were aimed at measuring the response of both the steel deck and each array of suspension elements. After the measurement of the response of the steel deck, the authors report on a second acquisition geometry, aimed at recording the response of each array of inclined stays and suspension cables, the radar was placed, at the level of the bridge deck, in the close neighbourhood of each side of the two towers (Fig. 3). The experimental set-up has been repeated for both sides of the two towers, for a total of four measurement positions.

Figure 3. Ibis-S system installed close to the masonry pier to measure the displacements of stays and suspension cables of the Amposta bridge. (after Gentile et al. 2014).

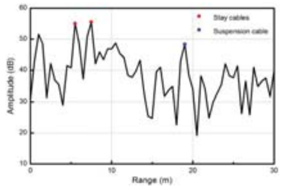

Figure 4. Radar range profile of the test scenario provided by the stays and the main suspension cables (after Gentile et al. 2014).

Observing the arrays of suspension elements, the range profile contains a few peaks since few reflecting elements, corresponding to the stays and the suspension cables, are encountered along the path of the electromagnetic waves: see figure 4. Only the first two stay cables were clearly detected in the range profiles of each array. The reason is related to the distance of the stay cables along the radar LOS. The two stays closer to the tower, about 2.0 m apart, are clearly distinguishable through a couple of well-defined and well separated peaks while the successive three stays, only 1.0 m apart, are not individually detected. Hence, the experimental evidence shows that, although the minimum range resolution of the radar interferometer is in principle equal to 0.5 m, the minimum distance required in the practice to individually detect two targets in a range profile needs to be larger than twice the minimum range resolution (i.e. 1.20-1.5 m).

The first two inclined stay cables of each four arrays were clearly identified in the radar survey: figure 5 shows the ASD associated to the ambient responses of stay cable 2 on one of the arrays. From the radar measurements the natural frequencies of each stay cables were estimated.

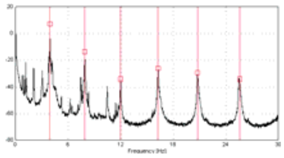

Figure 5. Auto-spectra (ASD) of the displacement measured from one of the stay cable (After Gentile et al., 2014).

The situation could improve with a radar operating over a wider bandwidth, as a sensor working at K band (24 GHz) which can usually provide bandwidth up to 1.5 GHz that translates into a nominal range resolution of 10 cm, instead of the 50 cm of the used radar. In this case all the stay cables could be detected and monitored.

It is worth noting that in the case where the radar data are used for estimating the tension force of the cable as in Gentile & Ubertini (2012), it is of main concern to distinguish each cable separately.

In addition, at this band low-cost high-performance radar transceiver are available, as commented in Cunlong et al. 2014.

3.2 *A challenging measurement*

To measure the vibration displacements expected from a building under ambient test, whose values can be down to a few microns, a very high sensitivity is necessary. In Negulescu et al. 2013, the authors compare radar measurements, conventional contact sensors and modelling acquired during the monitoring of an urban building. The investigated building gets a reinforced concrete (RC) wall structure and it includes a double-basement, a ground floor and 10 storeys. The structure has a curved form consisting of a central building and two asymmetric wings, with different lengths and inclinations. The load-resistant structure consists of RC walls. The thickness of the RC walls varies between 25 and 70 cm. The walls are made of reinforced concrete C 20/25 that was cast in place. The height of each floor is 2.8 m except for the ground floor (4.5 m), and the total height of the building is 33 m (excluding the basement). The basement has two levels (2.8 m in height each).

Figure 6. Photo of the measured building (After Negulescu et al. 2013).

The foundation is continuous on the building contour and under the RC walls. Observing figure 7, where the range profile is compared to the simplified scheme of the building, only two bins have been selected for displacement retrieval, due to the not adequate signal to noise ratio of the other bins. These make the comparison among radar data and conventional sensor limited. The following figure 8, where the first mode reconstruction is shown for the three approaches, can benefit only of two points in the radar case.

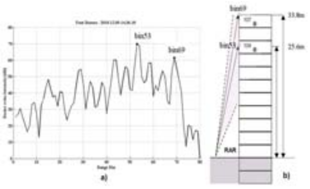

Figure 7. Range profile and building scheme identifying the analyzed radar bins (After Negulescu et al. 2013).

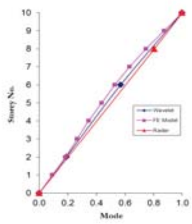

Figure 8: Mode shape of the structure for the based on seismometer, radar records and numerical modelling (After Negulescu et al. 2013).

In this second case, we can underline that due to the small amplitude of the displacements, the number of useful radar bins is limited. The use of a higher frequency could increase the signal to noise ratio, also thanks to the possibility to use antenna with higher gain without compromising the handiness of the sensor. In addition the sensitivity and accuracy of the measurement could be also improved decreasing the measured wavelength, i.e. increasing the frequency.

4 ADVANCED SYSTEMS

In the last years some attempts have been made to improve the performances and capability of radar sensors dedicated to vibration monitoring. Reducing the costs of the systems, and making a more user friendly apparatus are the main objectives of two recent papers. Here we recall two papers from recent literature.

In the first one, Cunlong et al (2014) present a prototype working at K band (frequencies belonging to the interval 18 GHz - 27 GHz), a frequency a bit higher of the Ku ones. The authors claim the goal of a FMCW radar prototype that is designed and fabricated based on an off-the-shelf radar frontend: in fig.8 a simple scheme taken from the paper is shown. Although they use higher operating frequency, the bandwidth is not augmented (300 MHz); they analyze the joint use of a net of different sensors which could allow an estimate of the displacement from different direction, achieving a vectorial measurement of the displacement.

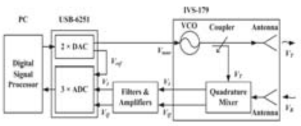

Figure 9. Scheme of the prototype discussed and developed in Cunlong et al. 2014 (After Cunlog et al. 2014).

This aspect is of very important for the study of the dynamic response of structures but demands an accurate synchronization. The experimental test is confined to a field test based on artificial targets, a situation apt for sensor characterization but far from a real monitoring.

A different approach is the one proposed by Papi et al. 2014. Here the authors report on the development and test of a handy, user friendly an moderate cost system for monitoring structures as bridges, towers, streetlight and floors. A simple measurement procedure is developed to provide a portable equipment for the engineering studies. The prototype has been tested in laboratory conditions and in a preliminary in-field measurement session on a streetlight. The sensor operates at X band, a frequency lower than that of Ibis-S the system by IDS

The data acquisition and processing is made using analysis cheap 8-bit analog to digital converter and a tablet controls the radar through a Bluetooth link. An Android app gives the start and the end of measurement, it saves the acquired data, and it calculates the FFT and plots the result. A more advanced processing has been implemented with a Matlab GUI, which provides the targets displacement with respect its equilibrium position and its oscillation frequency.

The system has been developed with the objective of maintaining a low cost, addressing towards the goal of a commercial apparatus whose performances are not improved with respect to those of the presently available systems. In addition, as in the previous case, the tests is carried out in laboratory and in the simple case of a streetlight. In this case the measurement conditions are not challenging from the radar point of view: a single target and with large displacement amplitude is monitored, where accuracy and spatial resolution issues are not stressed. A picture of the proposed equipment under test is shown in figure 10.

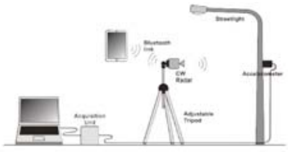

Figure 10. Scheme of the prototype discussed and developed in Papi et al., 2014 (After Papi et al. 2014).

5 CONCLUSIONS

In this paper a brief summary of the state of the art of the instrumentation available for the monitoring of Civil Engineering structures based on radar interferometry is first introduced, and a description of the working principle of the technique follows. The authors try to summarize the main technical features of the available radar sensors, how they are linked to the final performances of the system in terms of spatial and temporal resolution achievable through this technique. Two experimental tests related to a bridge and an urban building taken from recent literature have been analysed to underline the need to improve the performances of the available systems.

Finally two advanced sensors recently described in literature have been discussed. As far as these novel systems presented in recent literature is concerned, although the innovative characteristics, they seems not to introduce significant improvements from the application point of view. In particular, they do not disclose all the potential of the currently available microwave technology, leaving room for further improvements in terms of better accuracy and data analysis for the use of these systems for ambient tests.

REFERENCES

Atzeni C., A. Bicci, D. Dei, M. Fratini, M. Pieraccini (2010), Remote survey of the leaning tower of Pisa by interferometric sensing, IEEE GRSL7(1)(2010) 185–189.

Brincker R., L. Zhang and P. Andersen (2000), Modal identification from ambient responses using frequency domain decomposition, Proc. IMAC-XVIII, San Antonio, USA, 2000.

Coppi F., Gentile C. and Ricci P. (2010), A software tool for processing the displacement time series extracted from raw radar data, Proc. of the Ninth International Conference on Vibration Measurements by Laser and Non-contact Techniques, Ancona, Italy;22–25 June2010. AIP Conference Proceedings 1253, E.P. Tomasini (Ed.).

Cunlong Li, Weimin Chen, Gang Liu, Rong Yan, Hengyi Xu and Yi Qi, A Noncontact FMCW Radar Sensor for Displacement Measurement in Structural Health Monitoring. Sensors 2015, 15, 7412-7433; doi:10.3390/s150407412

Farrar C., T.W. Darling, A. Migliorini, W. E. Baker (1999), Microwave interferometer for non-contact vibration measurements on large structures, Mech. Syst. Signal Process.13 (2) 241–253

Gentile, C. and Bernardini, G. (2008), Output-only modal identification of a reinforced concrete bridge from radar-based measurements. NDT&E International 41(7): 544-553

Gentile C., Luzi G. (2014), Ambient vibration testing of the Amposta cable-suspended bridge by microwave remote sensing. Proceedings of the 9th International Conference on Structural Dynamics, EURODYN 2014; Porto, Portugal, 30 June - 2 July 2014.

Gentile C., Ubertini F. (2012) Radar-based dynamic Testing and System identification of a Guyed Mast, Tenth International Conference on Vibration Measurements by Laser and Noncontact Techniques — AIVELA 2012 Ancona, Italy 27–29 June 2012, ISBN978-0-7354-1059-6 ISSN0094-243X pp 318- 325.

Grazzini G., M. Pieraccini, D. Dei and C. Atzeni, (2009), Simple Microwave sensor for remote detection of structural vibration Electronics Letters 21st May 2009 Vol. 45 No. 11.

Luzi G., O. Monserrat, M. Crosetto (2012), The potential of coherent radar to support the monitoring of the health state of buildings, Res. Non-Destruct. Eval. 3 Issue 23 125–145.

Luzi G., M. Crosetto, M. Cuevas-González (2014), A radar-based monitoring of the Collserola Tower   (Barcelona). Mechanical Systems and Signal Processing 49 2014, pp. 234–248.

Negulescu C., G. Luzi, M. Crosetto, D. Raucoules, A. Roullé, D. Monfort, L. Pujades, B. Colas, T. Dewez (2013). Comparison of seismometer and radar measurements for the modal identification of civil engineering structures, Eng.Struct.V.51 10–22.

Papi F., Donati N., Pieraccini M. (2014), Handy Microwave Sensor for Remote Detection of Structural Vibration. EWSHM - 7th European Workshop on Structural Health Monitoring, Jul 2014, Nantes, France.

Pieraccini M., D. Tarchi. H. Rudolf, D. Leva, G. Luzi, C. Atzeni (2000), Interferometric Radar for Remote Monitoring Building Deformations, Electronics Letters, Vol. 36, No. 6, p. 569-570 2000. DOI: 10.1049/el:20000475 , ISSN 0013-5194, Online ISSN 1350-911X.

Pieraccini M., G. Luzi, D. Mecatti, L. Noferini, C. Atzeni, (2003), A microwave radar technique for dynamic testing of large structure, IEEE Trans. Microwave Theory Tech.51 No.5 1603–1609.

Pieraccini M., F. Parrini, M. Fratini, C. Atzeni, P. Spinelli (2008), In-service testing of wind turbine towers using a microwave sensor, Renewable Energy 0960-148133(1)(2008)13–21.(URL).

Rödelsberg S., L. Wendolyn , C. Gerstenecker, M. Becker, (2010), Monitoring of displacements with ground-based microwave interferometer; IBIS-S and IBIS-L, J. Appl. Geodesy 4 41–54. DOI101515/JAG.2010.005.

Skolnik M., “Radar Handbook” (1990), New York: Mc Graw Hill Publishing Company (1990), ISBN 0-07-057913-X.

Stabile T.A., Perrone A., Gallipoli M.R., Ditommaso R., Ponzo F.C. (2013), Dynamic survey of the Musmeci bridge by joint application of ground-based microwave radar interferometry and ambient noise standard spectral ratio techniques, 2013, IEEE GRSL 10 4 870–874, http://dx.doi.org/10.1109/ LGRS.2012.2226428.

SVS, ARTeMIS Extractor (2011), http://www.svibs.com, 2012.

Van Overschee P., B. De Moor (1996), Subspace identification for linear systems: Theory, implementation, applications, Kluwer Academic Publishers 1996.