Dynamic characterization of tower structures by means of interferometry measurements

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Abstract

The Aurelian Column has been investigated by the ENEA Research Center and NHAZCA S.r.l. (Spin-off company of "Sapienza" University of Rome) in order to characterize its dynamic properties for the assessment of its health status. In one day field work, a seismometric array made up of 24 short period (1 s) single channel sensors have been installed from the base of the column up to its top and centralized to a single acquisition unit. Two interferometric coherent radar sensors were also temporary installed at a distance of 25 m from the base of the column in the surrounding square in two orthogonal directions, in order to integrate seismometric data. Main achieved results on the dynamic characteristics of the column are: two dominating translational frequencies very close each to the other, 1.26 and 1.32 Hz. By the analysis of the modal shapes for the achieved resonance frequencies, an anomaly is detected at about 25 m height, thus driving to hypothesize a mechanical discontinuity of the structure.

1. Introduction

Aurelian Column has been object of several studies in past years aiming to characterize its health status, also considering the censed effects suffered by the structure following historical strong earthquakes (Clemente et al., 1988; Giuffrè, 1984; Giuffrè & Ortolani, 1988; Funiciello & Rovelli, 1998; Bongiovanni et al., 2014). In order to assess the dynamic properties of all the sectors of the column, field investigations were performed by the integration of contact and remote sensing techniques.

Specifically, a seismometric survey, performed by the installation of sensors on the column, was integrated by a Terrestrial Radar Interferometric survey (Pieraccini et al., 2008; Atzeni et al., 2010; Gentile & Bernardini, 2010; Cunha et al., 2001) in order to improve the investigation resolution and characterize the dynamic behavior of the structure also where contact sensors could not be installed for logistic issues. As also highlighted by Mazzanti et al. (2014), by the exploitation of advantages offered by both contact (e.g. 3D spatial information, high accuracy in the measurement of velocities, high sampling frequency etc.) and remote sensing techniques (e.g. continuous information on the whole visible part of the structure from the monitoring point, quick and non-invasive installation etc.), an accurate and low cost quick recognition of the static and dynamic properties of the structure can be achieved.

This paper describes the results achieved by the Operational Modal Analysis (Zhang et al., 2005; Peeters & Roeck, 2001; Brincker & Kirkegaard, 2010) performed on data collected by the above described integrated monitoring network and the preliminary interpretation about the structural and mechanical properties of the Aurelian Column.

2. The Aurelian Column

The Aurelian marble column is located in Piazza Colonna (Rome) just in front of Palazzo Chigi, seat of the Italian Prime Minister (Figure 1a). It is made up of 19 piled blocks carved to obtain a spiral staircase (called "cochlea"), connecting the central core to the outer ring of the structure. The overall height of the column is 29.6 m and its diameter is about 3.7 m. At the top of the column is the bronze statue of St. Paul, resting on a square pedestal of about 6 m and height of about 10 m.
By historical witnesses, seems that the structure suffered damages due to strong earthquakes and especially that of January 22nd, 1349, probably causing the dislocation and the sliding of some of the blocks that form the structure of the column (Figure 1b). Such evidence was firstly noticed by the Architect Domenico Fontana, during the first known restoration works of the column (Masiani & Tocci, 2010).

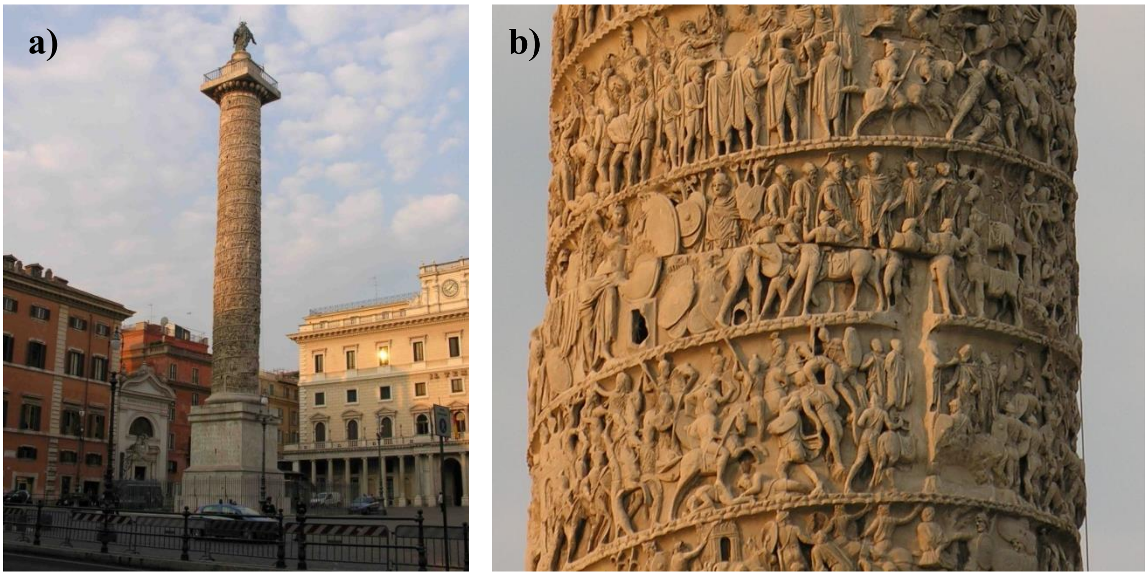

Figure 1. View of the Aurelian Column (a) and relative dislocation between the blocks (b)

3. Performed activities

An array of 18 short period (1 s) single channel Kinemetrics SS-1 seismometers (wire connected to a Kinemetrics Granite recorder) was installed in the spiral stair inside the column thus allowing the measurement of velocities along both the horizontal and vertical direction (Figure 2a). Furthermore, two additional seismometric terns (composed of three single channel Kinemetrics SS-1 sensors) were positioned close to two IBIS-S (by IDS S.p.A., Figure 2b) coherent interferometric sensors temporary installed on tripods in the surrounding square, at a distance of about 25 m from the column axis. IBIS-S sensors, able to simultaneously measure the displacements along the instrumental line of sight (LOS) of a large number of points along the structure by high sampling frequency (up to 200 Hz), were positioned in two orthogonal directions in order to impose the parallelism between the interferometric and the seismometric direction of measurement. In Figure 3, the monitoring layout scheme is depicted.
The interferometric and seismometric systems were synchronized by GPS and Network Time Protocols and started collecting data simultaneously at a 100 Hz sampling rate for a time interval of 20 minutes.

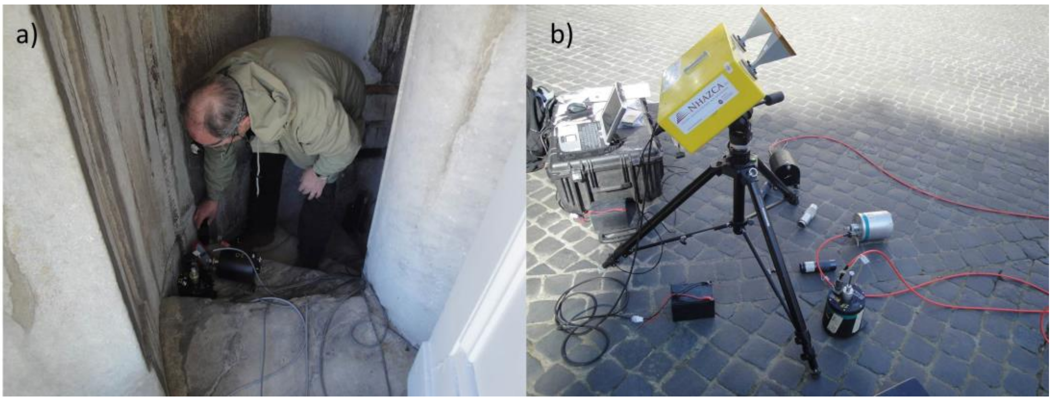

Figure 2. Kinematrics SS-1 seismometers installed in the spiral stair inside the column (a) and one of the two IBIS-S interferometric monitoring platform, equipped with three seismometers (b)

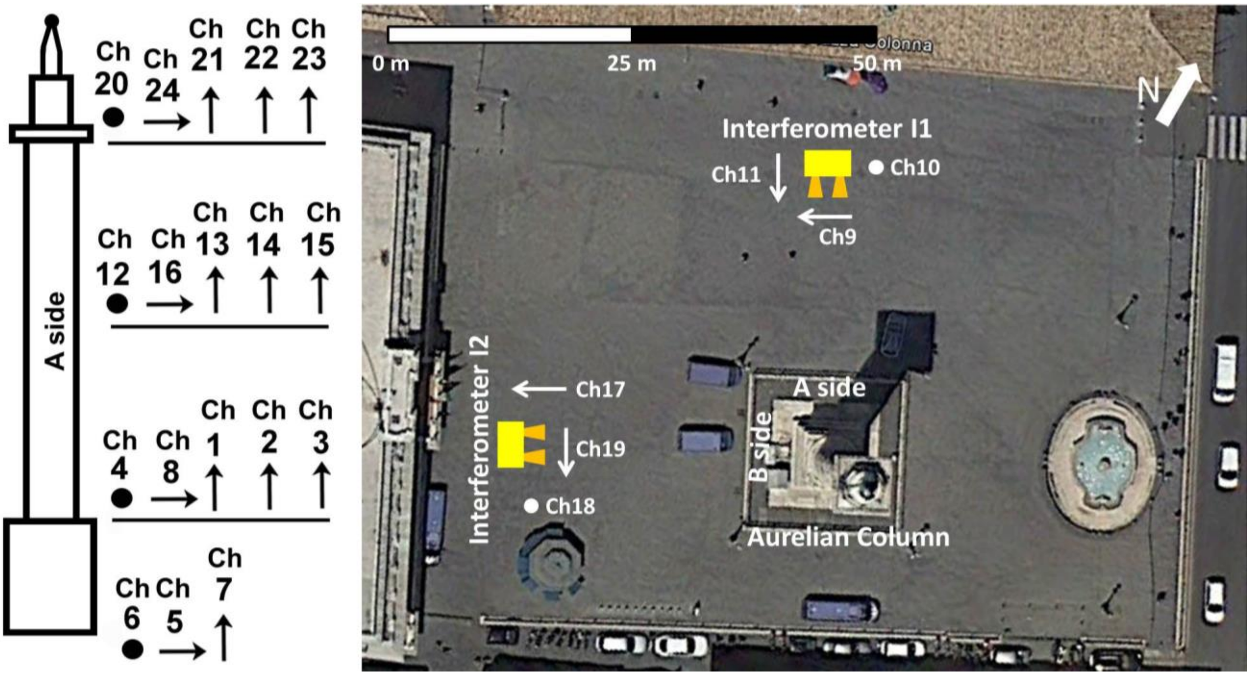

Figure 3. Seismometric and interferometric monitoring layout scheme

4. Achieved results

Data collected in the frame of field tests have been processed through official software and proprietary algorithms.

The interferometric recordings have been first examined with reference to the Signal to Noise Ratio (SNR), thus allowing the selection of the only pixel characterized by high reflectivity (i.e. high measurement accuracy). The power spectral densities of all the selected pixels, achieved by the registrations of both the interferometric radar sensors, are represented in Figure 4.

Since the raw interferometric data registered displacement in the only line of sigh (LOS) direction, the resulting displacement amplitudes of the selected pixel in the frequency domain were then projected along the horizontal direction by geometric projection in order to be compared with data collected by seismometers installed in the column.

By a preliminary and quick analysis, the most evident peak is identified at about 0.5 Hz; other peaks can be noticed, even if characterized by lower amplitude. By a detailed analysis, smaller peaks (characterized by smaller displacement amplitude) can be identified, on both interferometric registrations and on most of the selected pixel at a frequency of 1.26 Hz (for interferometer I1, Figure 5a) and 1.32 Hz (for interferometer I2, Figure 5b).

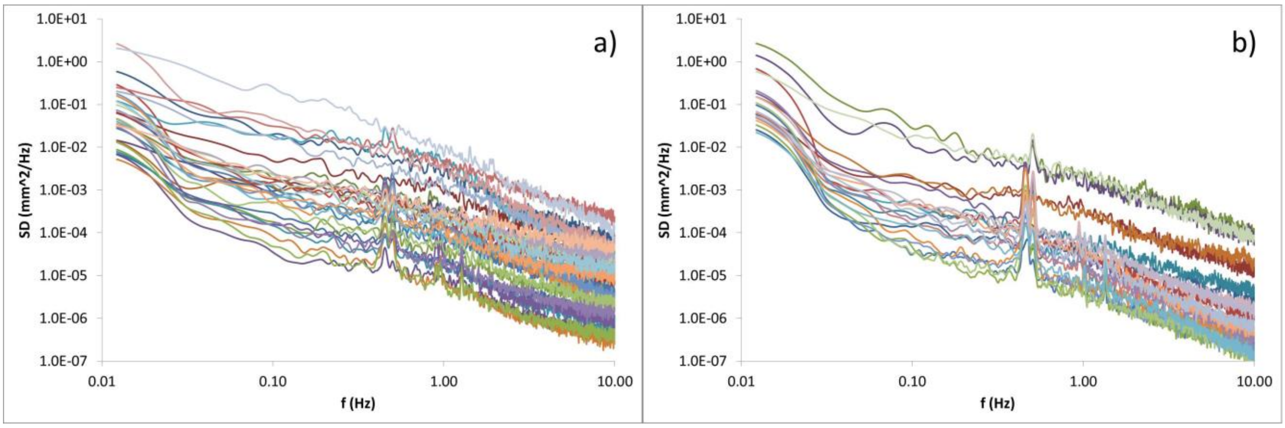

Figure 4. Spectral densities of the time histories recorded by the interferometric radar sensors I1 (a) and I2 (b)

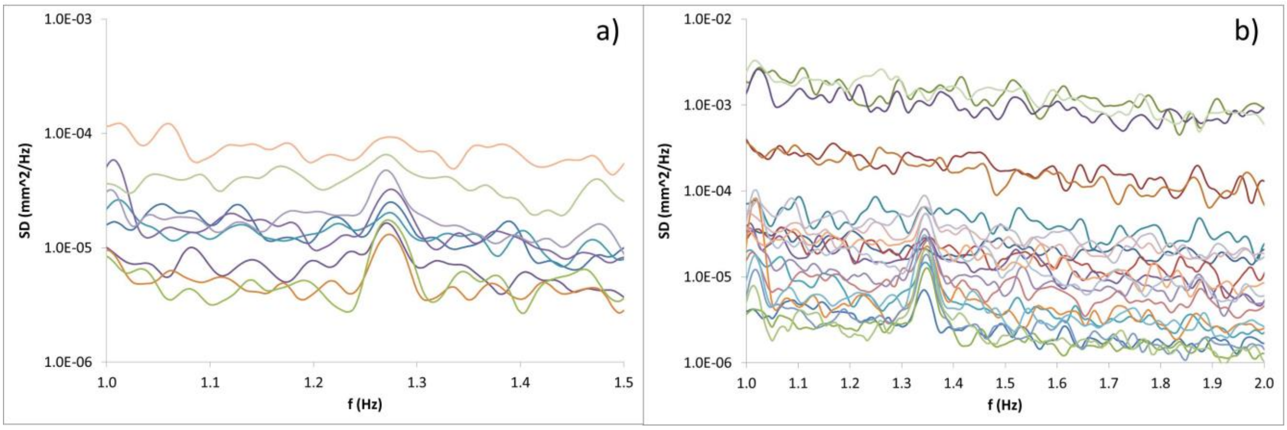

Figure 5. Details of the spectral densities achieved by the interferometric radar sensors I1 (a) and I2 (b) and identification of frequency peaks at 1.26 Hz (a) and 1.32 Hz (b)

Both the seismometers and the interferometric recordings were processed by means of cross spectral analysis with reference to translational frequencies and the same resonance frequency peaks (1.26 and 1.32 Hz) were identified thus confirming the outcomes of previous investigations and studies (Clemente et al., 1988; Giuffrè, 1984; Giuffrè, 1988; Funiciello & Rovelli, 1998; Bongiovanni et al., 2014).

In Figure 6, the resonance peaks identified by some of seismometers installed on the top of the column (ch20, ch24 and ch23) are identified, by way of example, on the frequency amplitude spectra diagram.

Seismometers horizontally aligned along the two main directions of the structure were also considered (ch06, ch04, ch12, ch20, and ch05, ch08, ch16, ch24, Figure 3). Cross spectral analysis has been performed by comparing each record with that on the top of the columns. The first outcome from this analysis is that while the amplitude coherence is very high (or rather good for the top-bottom couples), the angle of the cross spectrum is always out of phase and increasing going from the top to the bottom. By way of an example, the analyses for the couples ch16-ch24 and ch12-ch20 are reported in Figure 7. As a result of this analysis, modal shapes have been represented in Figure 8 for the two identified frequencies (1.26 and 1.32 Hz).

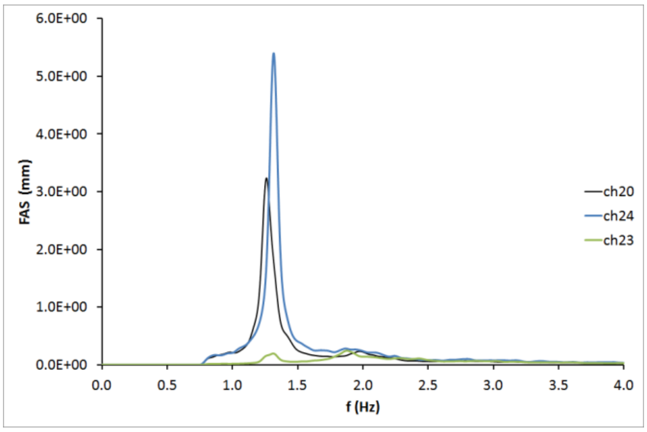

Figure 6. Fourier spectra achieved by the time histories of seismometers installed on the top of the column

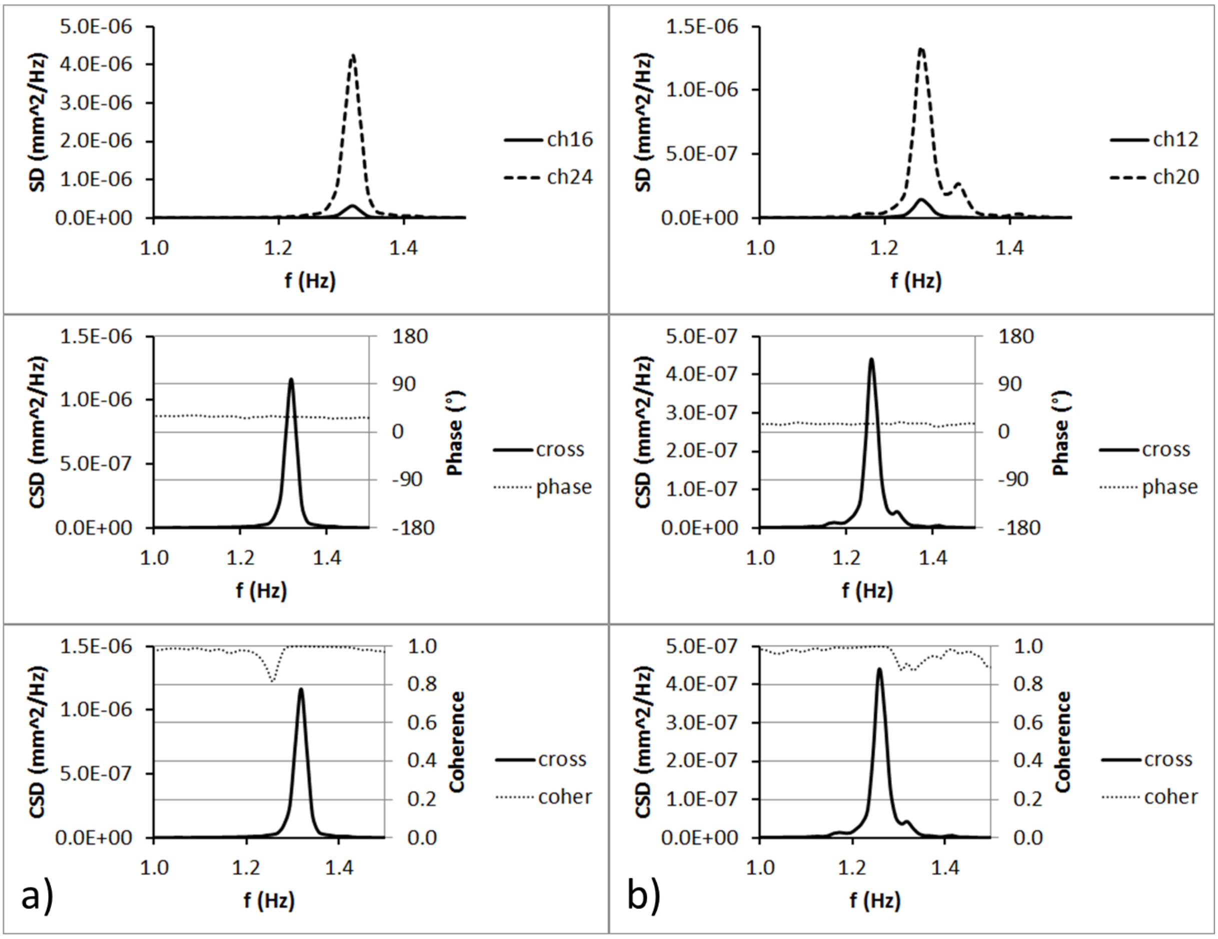

Figure 7. Example of cross spectral analysis performed on the seismometric couples ch16-ch24 (a) and ch12-ch20 (b) measuring in the same horizontal direction

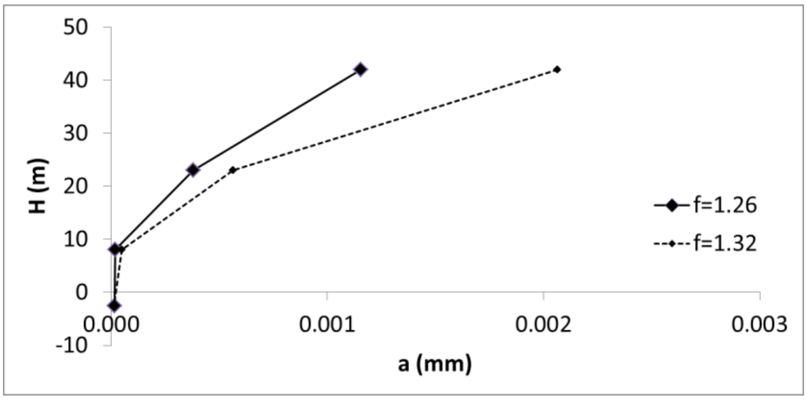

Figure 8. Modal amplitudes achieved by the analysis of seismometric data

Cross spectral analysis has been also performed on the time histories achieved by both the interferometric registrations. In Figure 9, by way of an example, the results achieved for a couple of pixel for each interferometer are reported.
In Table 1 are reported the pixel number, the pixel height and the phase angle and the coherence with respect to the top pixel, achieved by the signal processing of interferometric data for the identified frequency peaks (respectively: 1.26 Hz and 1.32 Hz).

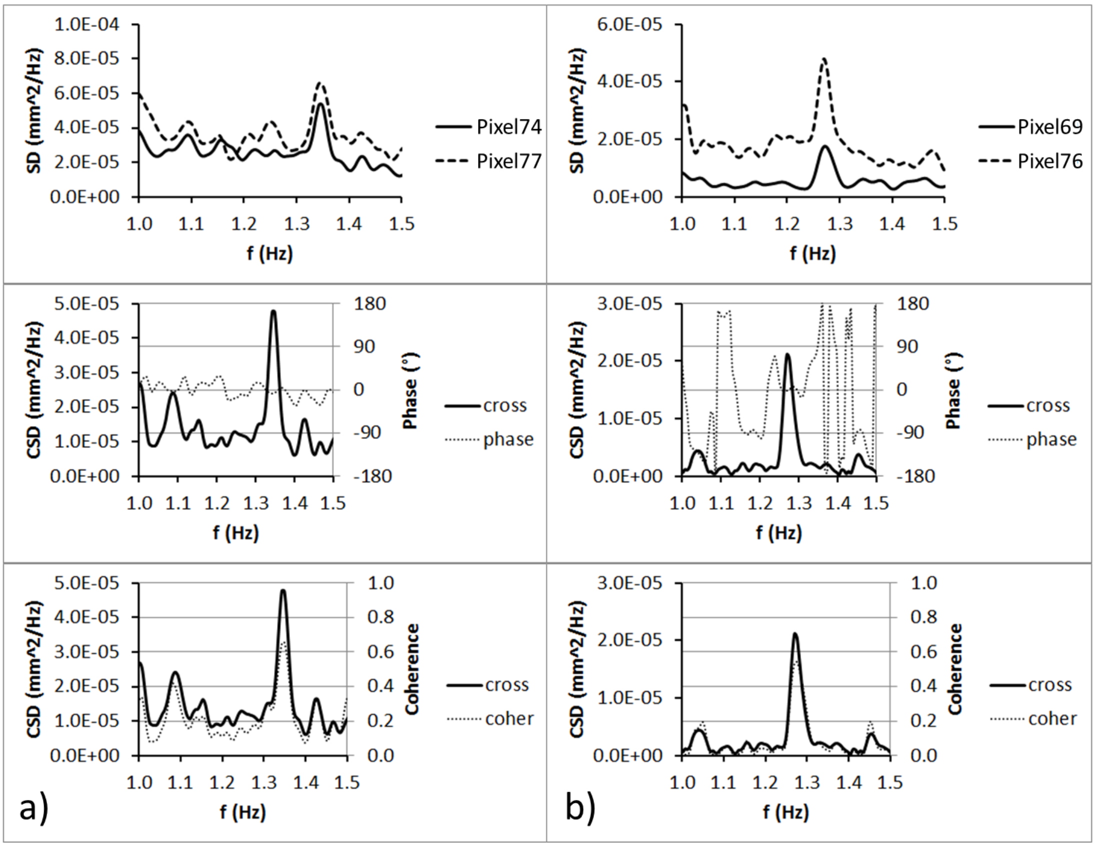

Figure 9. Examples of cross spectral analysis for records by interferometer I1 (a) and I2 (b)

Table 1. Main results achieved by the registrations of interferometer I1 (a) and I2 (b) for the frequency peaks, respectively, of 1.26 Hz and 1.32 Hz

a)

pixel	h (m)	phase °	coherence
60	17.3	-4	0.29
63	19.8	-9	0.53
65	21.4	-13	0.47
66	22.2	-15	0.50
67	22.9	-12	0.58
69	24.4	-8	0.51
71	25.1	-10	0.51
72	26.5	-14	0.43
74	27.9	-8	0.65
75	28.6	-8	0.53
77	29.9	-4	

b)

pixel	h (m)	phase °	coherence
61	18.1	-4	0.40
64	20.5	-11	0.47
65	21.3	-23	0.32
66	22.1	5	0.48
69	24.3	-2	0.53
70	25.0	-7	0.26
75	28.5	3	0.65
76	29.1		

In Figure 10, the spectral amplitudes associated with each interferometric pixel for the respective frequency peaks are plotted.
By the comparison of Figure 8 and Figure 10 can be noticed that both the modal amplitudes achieved by seismometric data and by data collected by the interferometer I2 (Figure 10b), experiment a slight change in the curvature around 25 m height.

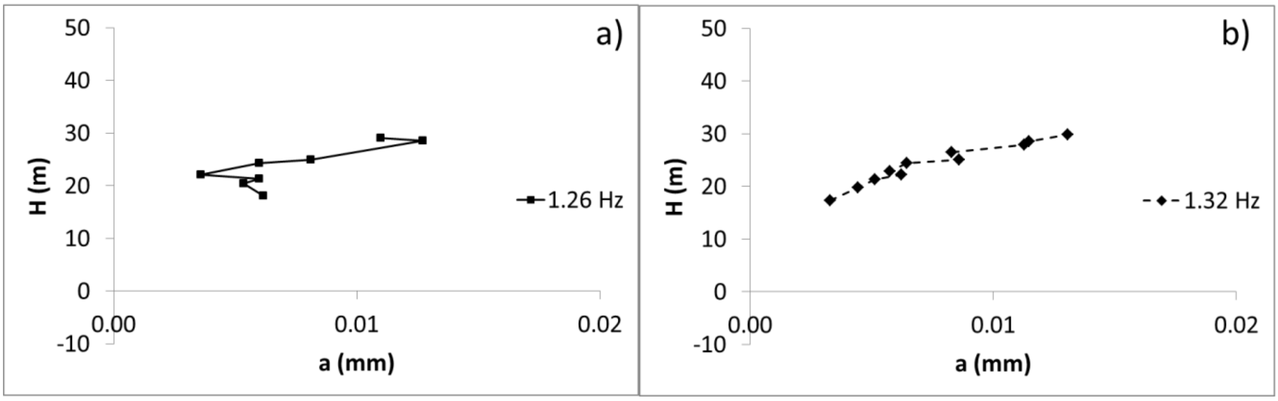

Figure 10. Modal amplitudes achieved by interferometer I1 for the frequency peak at 1.26 Hz (a) and by interferometer I2 for the frequency peak at 1.32 Hz (b)

5. Conclusions

Results achieved by the experimental tests described in the present paper, based on the integration of contact and remote sensing techniques, allowed to confirm the outcomes of previous studies and to drive some preliminary hypothesis about the mechanical characteristics of the Aurelian Column. The integration of seismometric and interferometric techniques, characterized by different operational principles, allowed the validation of the achieved results and the redundancy of information. The first vibration frequencies were identified at 1.26 and 1.32 Hz, depending on the measurement direction in the horizontal plane. The peaks at 0.5 Hz, identified in the only spectral densities of the time histories recorded by both the interferometric radar sensors, should be attributed to effects induced on the column by environmental noise, rather than to structural dynamic properties. Such an outcome can be demonstrated by the comparison with the spectral densities achieved by seismometric sensors installed near the interferometric radar sensors, showing a frequency content below 1Hz (more evident in the vertical sensors ch11 and ch19 and in the horizontal sensors ch09 and ch17), even considering the short period characteristic of seismometers and the applied band-pass filter 0.8-10 Hz (Figure 11).

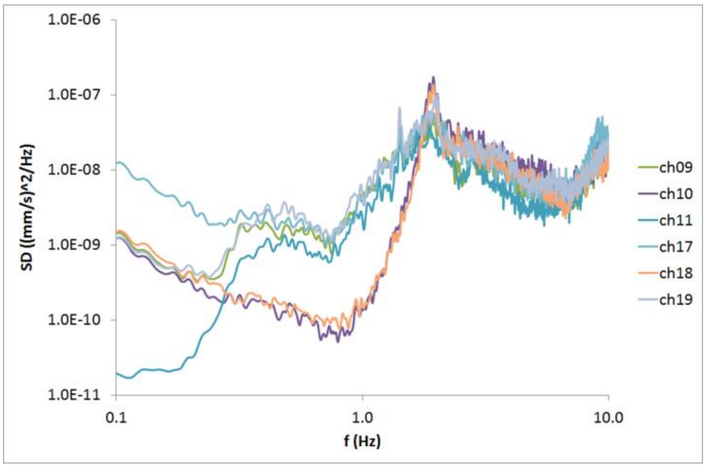

Figure 11. Spectral densities of the seismometers installed close to the interferometric radar sensors. The frequency content below 1Hz is interpreted as the source of the frequency peaks identified by the interferometric radar signals about 0.5 Hz

The most relevant outcome of the test is the slight change in the curvature of the modal amplitudes around 25 m height, achieved by both techniques. This evidence can be preliminary attributed to discontinuities in the mechanical properties of the structure due to the dislocations and the sliding of some of the blocks that form the structure of the column. Furthermore, the non-linearity of the mechanical properties of the structure (due to the discontinuities between the blocks forming the structure of the column) is also demonstrated by the cross spectral analysis of seismometric data, showing, despite high coherence values, cross spectral angles always out of phase and increasing going from the top to the bottom of the column.

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