Identification of modal parameters: radar measurements and of ambient vibrations measurements

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SUMMARY:
The paper presents the diagrams of instrumentation and the results obtained by two techniques of building ambient vibration measuring: Interferometric Real-Aperture Radar (RAR) and microtremor. This paper mainly discusses the capability of RAR technique to identify the modal properties accurately. Comparisons between, on one hand, the two measurement techniques and, on the other hand, a numerical model of the structure and the real observations, are presented.
Finally, a conclusion can be drawn that the RAR used for identification of modal properties of the structure by ambient excitation yields to a good agreement with results of the velocimeter and numerical model models. Further work will be related to the estimation of the damage of the structure since RAR directly measures the displacements of the structure.

Keywords: measures, existing building, Real-Aperture Radar Interferometry, ambient vibration

1. INTRODUCTION

Several approaches have been developed using data from ambient, forced vibration measurements and earthquake records. Among these approaches, ambient vibration tests can be performed with less labour, time and cost, because unlike forced vibration testing, the forces applied to the structure in ambient vibration testing are not controlled and there is no need of vibration source (Trifunac, 1972; Ventura et al. 2002; Wenzel and Pichler 2006). The structure is assumed to be excited by wind, traffic and human activity. Generally, the main purpose of conducting ambient vibration testing is to obtain the dynamic characteristics of a structure, its natural frequencies, corresponding mode shapes and damping estimates. The measurements, typically accelerations or velocities, are taken for a long duration in order to be sure that all the modes of interest are sufficiently excited.
Literature reviews on structural monitoring, methods for vibration measurements, detections on changes in several physical parameters of a system (such as natural frequencies, modal shapes and modal damping ratios) or the damage detection for structural systems are nowadays quite important. A sampling of such studies for the modal characteristics evaluation can be found in Blandford et al., 1968; Udwadia and Trifunac, 1973; Beck and Jennings, 1980; Beck et al. 1994. Moreover microtremor analysis has some others important applications : to validate modelling for linear analyses (Daniell and Taylor, 1999; Cunha at al., 2006), to highlight the phenomenon of soil structure interaction (Iiba et al., 2004; Mucciarelli, et al., 2004), to detect the change in several physical parameters of a system throughout its normal exploitation or after experienced an earthquake (Luco et al., 1987; Liu, 1995; Celebi, 1996; Sone et al., 1996; Masri et al., 1996; Celebi, M., 2000).
Recently, new concepts for record microtremors on buildings have been proposed. Such methods use ground based remote sensing techniques instead of seismometers or accelerometers and can be called "non-contact microtremor measuring methods". Uehan and Meguro (2004) presented a new method (based on laser technology) for quick damage inspection (post-earthquake assessment) of RC structures by using the damage judgment criteria based on the change of natural frequency and the

non-contact microtremor measuring method. For this, they use an improved Laser Doppler Velocimeter (LDV) that detects the relative velocity between LDV itself and the measuring object. Gueguen et al. (2009) used velocity measurements based on Laser remote sensing techniques for building frequency assessment and they compared the results with the seismometer sensors measurements.

The interferometric Real-Aperture Radar (RAR) technique was introduced in nineties as an operational tool for health monitoring of large civil engineering structures (Farrar et al., 1999). It reduces the cost of acquiring and operating. Furthermore, an interferometric RAR as compared to other remote sensing techniques has many advantages such that it is capable to measure relative movements with a submillimeter accuracy from distance up to a hundred of meters and also making it possible to measure in bad weather as during heavy precipitation. Due to all these advantages, it has received an increasing interest for health monitoring of structures in the last decade (Tarchi et al., 1997; Bartoli et al., 2008; Tarchi et al., 1999; Pieraccini et al., 2000; Pieraccini et al., 2004).

Several techniques are used for large structures (bridges, dams) with millimetric amplitudes including the innovative radar approach (Gentile & Bernardini, 2008). The paper deals with vibration of smaller amplitudes and investigate the potential of the radar interferometric technique in such conditions, by comparing the results with the ones of velocimeter sensors measurements; till now sub-millimetre amplitudes of displacement in similar conditions have been detected through interferometric radar but missing validation data (Luzi et al. 2012).

2. MEASUREMENT TECHNIQUES

Two different measurement techniques were adopted to monitor the selected building, located in Font Romeu (France) and described in details in the following section 3 of this paper: conventional velocimeter sensor measurements and RAR interferometric measurements. The main difference is that using velocimeters (or Laser) the velocities of the structure are measured while using Radar instrument the displacements are measured. In the latter case, more exactly, the displacements along the line of sight (LOS) are recorded.

3. BUILDING DESCRIPTION

The measured building is the central tower of the Font Romeu sportive complex that was conceived in 1966 by the French architect Roger Taillibert. The building (Figure 1) has a RC walls structure, with double-basement, ground floor and 10 storeys.

The structure has a curved form that can be described by a central part and two asymmetric wings with different lengths and inclinations. The resistant structure is composed by RC walls. The RC walls are continuous on the concave side and discontinuous on the other side. For the short wing and the central part the discontinuous RC walls are parallel with Y axe (X and Y orthogonal axis are defined by the most frequent wall orientations, X correspond to the direction of major length of the building), while for the long wing the discontinuous RC walls are perpendicular to the Y axe. The sensors are placed in order to have the North component parallel to the axe Y and the South component parallel the axe X. The staircase and the lifts are placed in the central part of the structure. The thickness of the RC walls varies between 25 and 70cm

The walls are made of cast in place reinforced concrete C 20/25. Height floor is 2.8 m, the ground floor has 4.5 m, and the total height of the building is 33m (without including the basement). The basement has two levels (having 2.8m height). The foundation is continuous on the building contour and under the RC walls. The structure is positioned near different buildings with smaller heights, but these structures should not influence the dynamic behaviour of the measured structure.

Figure 1. Measured building

4. MEASUREMENT SETUP

4.1 Microtremor measurements

For the microtremor measurements, the eight sensors are placed in two different configurations on the roof of the structure and on the height of the structure. For the roof configuration, three sensors are placed on the central part (107, 108 and 105), three sensors are placed on the shorter wing (103 and 104) and two sensors are located on the longer wing (102, 106 and 109). As the structure has an irregular geometry (from geometrical and rigidity point of view) with the RC walls positioned different from a part to another of the structure, the aim of this configuration is to determine the predominant frequencies in both directions for each part of the structure; central part, and the two wings.

For the height configuration the sensors are placed as follows: 105 on the ground, 106 on the level -2 (basement), 102 at the second level, 108 at the third level, 103 at the fifth level, 108 at the seventh level, 104 at the ninth level and 107 at the eleventh level. For this configuration the sensors 105, 103 and 104 do not record. The main objective of this configuration was to determine the shape mode of the central part of the structure and to check if there is a SSI effect. Unfortunately, as the sensor on the ground did not record, the later objective regarding SSI effect cannot be checked. Anyway, this issue is not the purpose of the current paper, for which the objective is to compare the contact and non-contact results and not to investigate the SSI effects. The sensors positions are presented in the Figure 3 for roof configuration and Figure 2 for height configuration.

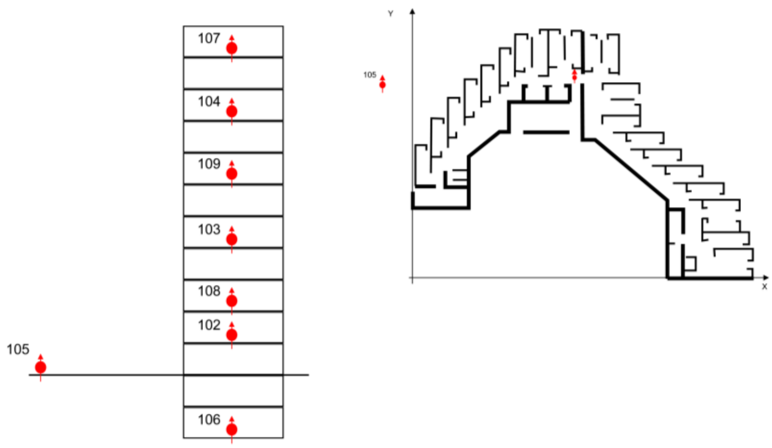

Figure 2. height configuration

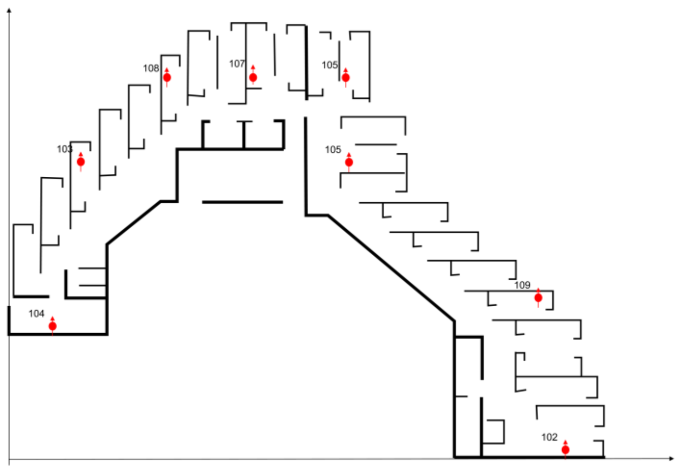

Figure 3. roof configuration

4.2 RAR measurements

The acquisition geometry used in the Radar monitoring of the building is dictated by the radar position: different ranges and angles have been tested to search for the highest SNR. Data here discussed refers to a position of the RAR at 7 meters distance from the façade, with a LOS direction at an elevation angle with respect to the horizon, θ, approximately ranging from 72º to 82º. Fig 4 shows a simplified scheme of the radar view. With such geometry, the measurable component of the displacement d_{LOS} is given by:

$$d_{LOS} = \Delta S \frac{L}{R} = \Delta S \cdot \cos(\vartheta) \tag{1}$$

where L is the distance between the radar position and the building, R is the slant range, and ΔS is the actual displacement.

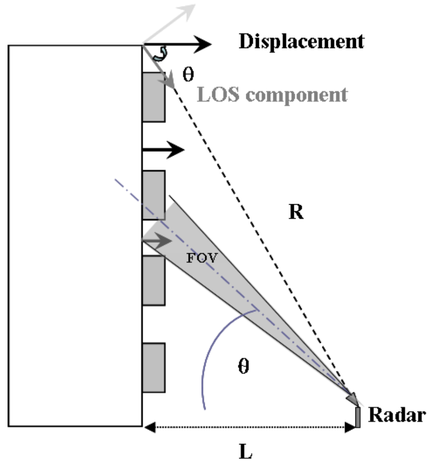

Figure 4. Typical radar acquisition geometry; FOV: field of view of the radar system, L distance between RAR and the building; θ elevation angle

5. COMPARISON OF THE MEASUREMENT TECHNIQUES

For the comparison of the records obtained through the two measuring techniques, due to its higher SNR, BIN53 situated at 9th level is used for the radar and sensor 107 for the microtremor measurements.

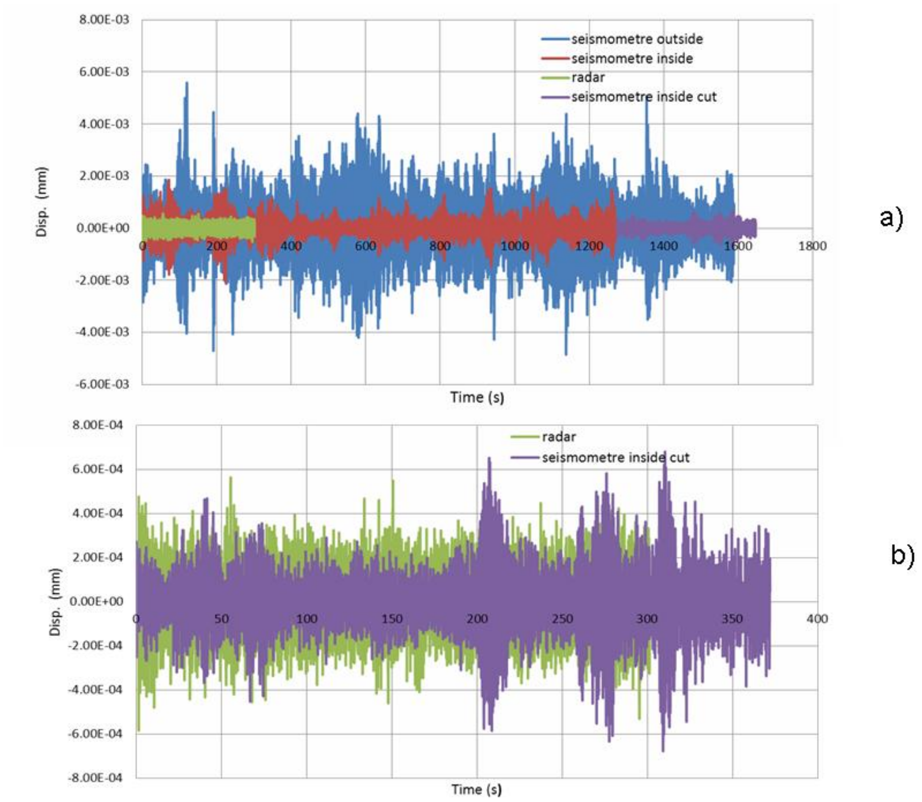

Figure 5. Comparison between microtremor and radar measurements in terms of displacement for the record corresponding to the top of the structure

The radar location only allowed measuring vibration along one direction associated with the North direction of the microtremor sensors. Figure 5 shows a comparison between the displacement recorded directly with radar instrument and the displacement obtained from the integration of the velocity recorded with the velocimeter. In the Figure 5 are represented the displacements of the seismometer located outside on the top of the structure (seismometer outside), the seismometer located inside at the highest storey of the structure (seismometer inside) and the radar displacement.

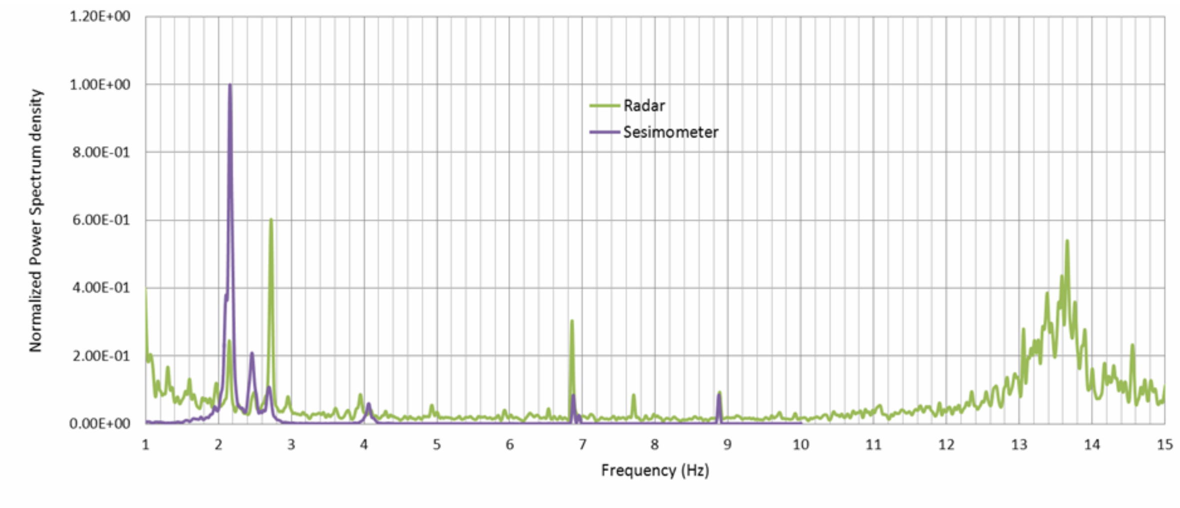

Figure 6. Comparison of the normalized power spectral density functions from the records by radar remote sensing technique (BIN53-green line) and velocimeter sensor (# 107-violet line)

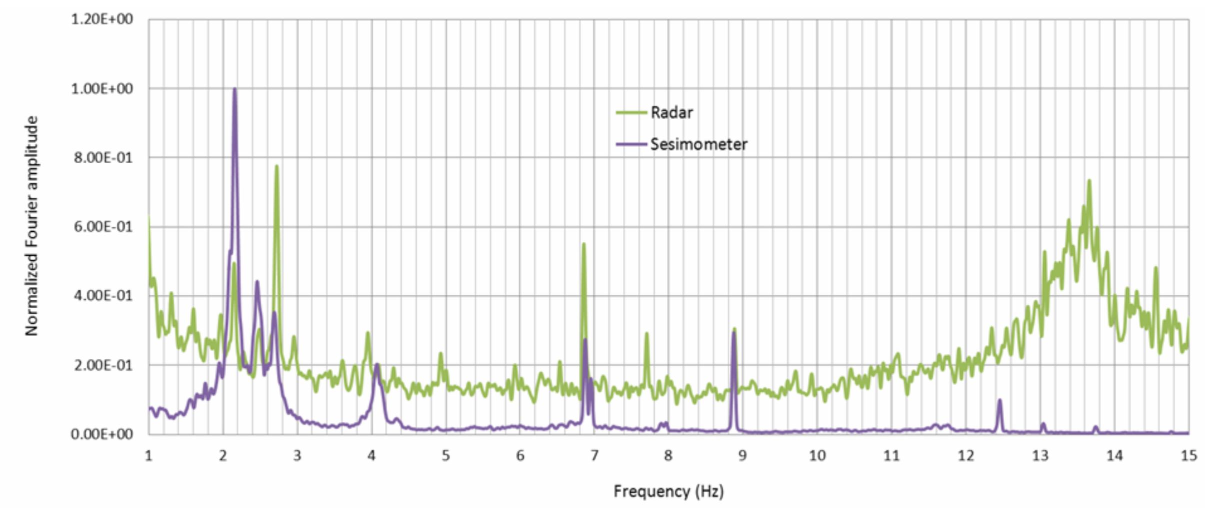

Figure 7. : Comparison of the normalized Fourier spectrum from the records by radar remote sensing technique (BIN53-green line) and velocimeter sensor (# 107-violet line)

The seismometer outside and the seismometer inside the structure at the top level did not measure at the same time. As expected, the noise level of the signal outside the building is higher than the one inside the building. The signal inside the building and the radar signal show comparable values. In order to compare the frequencies and to determine the mode shape of the structure, we processed the radar Time Series and, for the seismometer, the last part of the signal recorded inside the structure. These signals are compared in the Figure 5b). Before processing of both recorded displacements, a band-pass filter (0.3Hz-20Hz) was applied. Figure 6 presents the normalized power spectra and Figure 7 normalized amplitude spectra for the radar and microtremor measurements. It can be noticed that the three predominant frequencies of the structure were identified by both measurement techniques: 2.14, 2.46 and 2.72Hz. Moreover, higher vibration mode frequencies of the structure are well identified: 6.8 and 8.8Hz.

The frequency corresponding to the torsional mode at around 4.05Hz seems to be little shifted for BIN53. In addition in Figure 6 the PSD corresponding to BIN 69 shows a 4.05 Hz peak: taking a mean value between the two data, the 0.05 Hz error is of the order of frequency accuracy available from the radar technique. The location of the measurements points can also explain the differences of the amplitude that are noticed to the three predominant frequencies. The microtremor sensor is placed inside the central part but not inside the rigid core formed by the reinforced concrete walls of the staircase and the elevator. This rigid part is related to the left wing that has the predominant frequency of 2.7Hz, while the central part outside the rigid core present similar behaviour with the right wing that has the predominant frequency of 2.1Hz. The radar measuring directly on the wall of the rigid core show more amplified the frequency of 2.7Hz. Moreover, the higher frequencies of the structure of 6.8 and 8.8Hz are well detected by the radar measurements. Figures 6 and 7 show a good agreement between the two techniques to assess the frequencies of existing building.

The non-normalized spectra of radar and velocimeter measurements show different amplitudes with a scaling factor of about 10. This difference is reasonable because the radar processing includes windowing and filtering missing data normalization, so during the processing energy is loss.

To go further with the intercomparison of the methods, we propose to check them against a simple numerical model. Mode shapes from each source will be reformulated are estimated through the wavelet transforms (Le and Tamure, 2009; Wijesundara et al., 2012) of output response at point k and the reference point as shown below:

$$\phi_i^k = \frac{W_x^k(a_i,\tau)}{W_x^{ref}(a_i,\tau)} \tag{2}$$

For the modal shape using radar records we treated BIN 53 situated at 8^{th} story and BIN 69 situated at the top of the structure. For the microtremor measurements we use sensors 108 situated at the 2^{nd} level, sensor 109 situated at the 6th level and sensor 107 situated at the top of the structure.

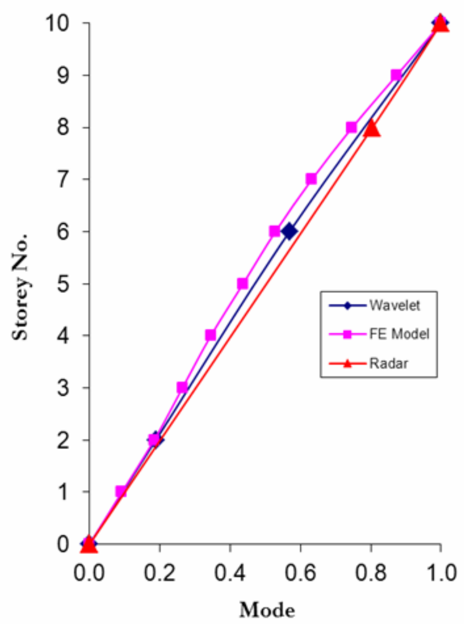

Figure 8. Modal shape of the structure in North-South direction coming from microtremor record and numerical model

In the framework of interreg ISARD project, the same building was modelled by CSTB (Taillefer and

Delmotte, 2006). The two predominant frequencies obtained by the numerical modelling fit quite well the frequencies obtained by the two measurement techniques. CSTB document shows the mode shape corresponding to the first mode of vibration of the structure presented in Figure 8. The study does not give supplementary information of the periods corresponding to the higher vibrations mode of the structure.

Table 1 shows the frequencies values obtained using microtremor measurement, radar measurement and numerical modelling.

Table 1. The main frequencies values obtained using microtremor measurement, radar measurement and numerical modeling in North-South direction (axe Y)

Method	Frequencies (Hz)				
	1	2	3	4	5
Microtremor measure	2.14	2.72	4.05	6.8	8.8
Radar measure	2.14	2.72	3.95/4.05	6.8	8.8
Numerical modelling	2.22	2.76	-	-	-

5. CONCLUSIONS

In this paper, we assessed the potentiality of RAR instrument for measuring building vibration by comparing the results with microtremors measurements results. The RAR measurements allowed evaluating correctly the modal information even in the case of an irregular building, as is the case of the observed building. The fifth periods of vibration presented in the Table 1 are almost identical with both technics. Moreover, RAR instrument measures the higher modes of vibration of the building. The first mode shape is similar using the records from radar and microtremor measurements. These promising results were obtained without any retro-reflector on the structure for radar measuring and without any solicitation except the ambient noise.

The RAR and microtremor measurements are complementary. RAR instrument implementation is very fast and the measurements can give more global information of the structure with respect to the point-wise microtremor sensor. The RAR can measure in specific points of the structure that cannot be accessible for installing velocimeter instruments. One of the advantages of RAR instrument that will be investigated in a further work is that it measures directly the displacements of the structure, which are related to the damage of the structure. For measuring the vibration of a structure, RAR is working at the highest level of precision of instrument. The installation of the velocimeter instruments is longer, but the record is not affected by spurious vibrating targets as is, in the case for RAR measurements where, due to a limited spatial resolution, they can add unexpected contributions; for this reason RAR data demands a fine analysis and radar bins with the highest SNR. On the other hand the interpretation of the velocimeter record is easier because the measurements are less sensitive to the external conditions and noise.

Until now, radar instruments were widely used to measure structures with milimetric amplitude, but this paper shows that the RAR instrument can be successfully used for the structures with vibration amplitudes around the micron.

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REFERENCES

Bartoli G., Facchini L., Pieraccini M., Fratini M., and Atzeni C., 2008. “Experimental utilization of interferometric radar techniques for structural monitoring,” Struct. Control Health Monit., vol. 15, no. 3, pp. 283–298.

Beck J.L. and Jennings P.C. 1980. "Structural identification using linear models and earthquake engineering records." Earthquake Engineering and Structural Dynamics: 145-160.

Beck, J. L., B. S. May, and D. C. Polidori (1994). Determination of Modal Parameters from Ambient Vibration Data for Structural Health Monitoring. In FirstWorld Conference on Structural Control, Los Angeles, California, USA.

Blandford, R., V. R. McLamore, and J. Aunon (1968). Analysis of Millikan Library from Ambient Vibrations. Technical report, Earth Teledyne Co.

Celebi, M. - Seismic Instrumentation of Buildings, Open-File Report 00-157 USGS, Menlo Park, California, 2000

Celebi, M., “Before and after retrofit – response of a building during ambient and strong motions”, Journal of Wind Engineering and Industrial Aerodynamics, 77 and 78, 259-268, 1996

Coppi F., Gentile C. and Ricci P. 2010. A software tool for processing the displacement time series extracted from raw radar data. Proceedings of the 9th Int. Conference on Vibration Measuerements by Laser and non-contact Techniques and short Course, Ancona, Italy. AIP Conference Proceedings 1253, ed. E.P. Tomasini.

Cunha Á., Caetano E., Magalhães F., Moutinho C., 2006. FROM INPUT-OUTPUT TO OUTPUT-ONLY MODAL IDENTIFICATION OF CIVIL ENGINEERING STRUCTURES, SAMCO.

Daniell W. E. and Taylor C. A., 1999. Effective ambient vibration testing for validating numerical models of concrete dams Earthquake Engineering & Structural Dynamics, Volume 28, Issue 11, pages 1327–1344.

Ewin, D. J. 1984. Modal Testing: theory and practice: 24-25. Taunton: Research Studies Press Ltd.

Farrar, C.R., Darling, T.W., Migliorini, A., Baker, W.E., 1999. ‘Microwave interferometer for non-contact vibration measurements on large structures’, Mechanical Systems and Signal Processing, Vol. 13, pp. 241-253.

Gentile and Bernardini G., 2008. Output-only modal identification of a reinforced concrete bridge from radar-based measuerements, NDT&E International, 41 pp. 544-553.

Gèradin, M. & Rixen, D. 1994. Mechanical Vibrations. New York: John Wiley & Sons, Inc.

Gueguen P., Jolivet V., Michel C. and Schveitzer A.-S., 2009. Comparison of velocimeter and coherent lidar measurements for building frequency assessment, Bulletin of Earthquake Engineering, Volume 8, Number 2, 327-338, DOI: 10.1007/s10518-009-9137-2.

Guralp http://www.guralp.com/

Hamamoto, T., Yu, J., Mori, H. (1997), “Seismic vulnerability assessment of building structures using microtremor measurements“, Proc. of the 7th ICOSSAR, Vol.3, pp1611-1618.

Inman, D.J. 1989. Vibration with Control, Measurement and Stability, Prentice Hall, Englewood Cliffs

ISARD http://www.isard.net/

Iiba M., Watakabe M., Fujii A., Koyama S., Sakai S. and Morita K., 2004. A Study on Dynamic Soil-structure Interaction Effect Based on Microtremor Measurement of Building and Surrounding Ground Surface, Proceedings Third UJNR Workshop on Soil-Structure Interaction, Menlo Park, California, USA.

Le T. H., Tamura Y., “Modal Identification of Ambient Vibration StructuresUsing Frequency Domain Decomposition and Wavelet Transform”, Proceedings of the 7th Asia-Pacific Conference on Wind Engineering, Taipei, Taiwan, November 8-12, 2009.

Liu P.L. "Identification and damage detection of trusses using modal data." Journal of Structural Engineering, ASCE 1995; 121-4: 599-608.

Luco J. E., Trifunac M. D., and Wong H. L. 1987. “On the apparent change in dynamic behavior of a nine-story reinforced concrete building”, Bulletin of the Seismological Society of America, Vol. 77, No. 6, pp. 1961-1983.

Luzi G., Monserrat O. & Crosetto M., 2012. The Potential of Coherent Radar to Support the Monitoring of the Health State of Buildings. To be published on April 2012 issue of Research in Nondestructive Evaluation, (ID: 660241 DOI:10.1080/09349847.2012.660241)

Masri S.F., Nakamura M., Chassiakos A.G. and Caughey T.K. "Neural network approach to detection of changes in structural parameters." Journal of Engineering Mechanics, ASCE 1996; 122-4: 350-360.

Meirovitch, L. (1970). "Methods of analytical dynamics." McGraw Hill, NewYork.

Mucciarelli, M. et al., “Analysis of RC building dynamic response and soil-building resonance based on data recording during a damaging earthquake (Molise, Italy, 2002)”, Bulletin of the Seismological Society of America, 94 (5), 1943-1953, 2004

Pieraccini M., Tarchi D., Rudolf H., Leva D., Luzi G., and Atzeni C., 2000. “Interferometric radar for remote monitoring of building deformations,” Electron. Lett., vol. 36, no. 6, pp. 569–570.

Pieraccini M., Luzi G., Mecatti D., Fratini M., Noferini L., Carissimi L., Franchioni G., and Atzeni C., 2004. “Remote sensing of building structural displacements using a microwave interferometer with imaging capability,” Nondestruct. Testing Eval. Int., vol. 37, no. 7, pp. 545–550.

Pieraccini M., Luzi G., Mecatti D., Noferini L., Atzeni C., 2003. A microwave radar technique for dynamic testing of large structure. IEEE Transactions on Microwave Theory and Technique, vol. 51, No. 5, May 2003, pp. 1603-1609.

Sone A., Yamamoto S. and Masuda A. "Identification of dynamic characteristics of structure and its change by using wavelet analysis of records of microtremor and response of structure on ordinary condition and during strong shock." Journal of Structural and Construction Engineering, AIJ(in Japanese) 1996; 490: 65-72.

Taillefer N. and Delmotte P., 2006. Building Typology and Vulnerability Assessment Level 2, ISARD Module 2 report CSTB-DSSF/ISTA / ISARD.

Tarchi D., Ohlmer E., and Sieber A., “Monitoring of structural changes by radar interferometry,” Res. Nondestruct. Eval., vol. 9, no. 4, pp. 213–225, 1997.

Tarchi D., Rudolf H., Luzi G., Chiarantini L., Coppo P., and Sieber A. J., 1999. “SAR interferometry for structural changes detection: A demonstration test on a dam,” in Proc. IGARSS, vol. 3, pp. 1522–1524.

Trifunac, M. D. (1972). Comparisons Between Ambient and Forced Vibration Experiments. Earthquake Engineering and Structural Dynamics 1, 133–150.

Udwadia, F. E. and M. D. Trifunac (1973). Ambient Vibration Tests of a Full-Scale Structure. In Preceedings, Fifth World Conference on Earthquake Engineering, Rome.

Uehan F. and Meguro K., 2004. Assessment of seismic damage to railway structures using applied element method and microtremor measurement, 13th World Conference on Earthquake Engineering Vancouver, B.C., Canada August 1-6, 2004 Paper No. 1407.

Uehan, F. and Nakamura, Y. (1996). “Ground motion characteristics around Kobe city detected by microtremor measurement -the great Hanshin earthquake disaster-“, Proc. of the 11th WCEE, Paper No.714.

Ventura C., Lord J.F., Simpson R., 2002. Effective Use Of Ambient Vibration Measurements For Modal Updating Of A 48 Storey Building In Vancouver, Proceedings of the 3rd International Conference on Structural Dynamics Modelling - Test, Analysis, Correlation and Validation - Madeira Island, Portugal.

Wenzel H., Pichler D., 2006. Ambient vibration monitoring, John Wiley & Sons, 308 pages.

Wijesundara K.K., Negulescu C., Foerster E., Monfort Climent D., 2012. “Estimation of modal properties of structures through ambient excitation measurements using continuous wavelet transform”, Engineering Structures, submitted.