Joint application of non-invasive techniques to characterize the dynamic behaviuor of engineering structures

T.A. Stabile, A. Perrone, M.R. Gallipoli, A. Giocoli, S. Pignatti, A. Palombo & S. Pascucci
National Research Conusil – Institute of Methodologies for Environmental Analysis

F.C. Ponzo, R. Ditommaso, A. Di Cesare, A. Mossucca, G. Auletta, D. Nigro
Di.S.G.G. – University of Basilicata, Italy -Potenza (9 pt)

SUMMARY

The present paper aims at analyzing the potentialities of a new technological approach for the dynamic characterization of civil infrastructures. The joint approach combines conventional, non-conventional and innovative techniques in order to set up a non-destructive evaluation procedure at a multi-scale and multi-depth levels (i.e. with different degrees of spatial resolution and different subsurface depths). The aim of this paper is the estimation of fundamental dynamic parameters of two bridges, selected as test bed site in the ISTIMES project (EU – 7th Framework Program), by the joint application of fast executable, non-invasive techniques. In particular for Sihlhochstrasse Bridge (Switzerland), Ground-Based microwave Radar Interferometer technique has been applied with a high-frequency thermal camera to measure the oscillations due to traffic excitations; for Musmeci bridge the microwave interferometry radar technology was jointly applied with a consolidate technique such as the Ambient Noise Standard Spectral Ratio.

Keywords: Engineering structures, non-invasive techniques, Ground-Based microwave technique, Ambient Noise Standard Spectral Ratio, High-frequency thermal camera.

1. INTRODUCTION

Determining a building's response to earthquake motions for risk assessment is a primary goal of seismologists and structural engineers alike (e.g., Cader, 1936a,b; Çelebi et al., 1993; Kohler et al., 2005; Clinton et al., 2006; Snieder and Safak, 2006; Chopra, 2007). The monitoring of such structures allows the identification of the dynamic characteristics and eventually their changes over time as a result of structural degradation; this is an important tool to evaluate the integrity of large infrastructure exposed to intense operational demands for long periods (Martire et al., 2010; Picozzi et al., 2010). Unfortunately, this method of risk assessment is limited by the amount of available data. Traditionally, the experimental methods used to estimate the structural characteristics of infrastructures and to evaluate the change due to the damage, consisted in the recording of the accelerometer responses of the structure during earthquakes, harmonic forcing, or shock tests (Dunand et al., 2004; Boutin and Hans, 2008). Starting from 1970s the ambient vibration method has known large developments (see Ivanovic et al., 2000 and references therein) due to its effectiveness and because it is not an invasive and destructive approach. In many studies using ambient vibrations from engineering structures (Carden and Fanning, 2004), frequency domain analysis is performed to determine modal frequencies and mode shapes, sometimes including damping ratios. Usually, it would like to see if there are variations in modal parameters before and after major earthquakes (Snieder et al., 2007) or before and after retrofitting (Celebi and Liu, 1998). A step forward is the monitoring of infrastructures by measuring the ambient vibration using remote sensing instruments instead of contact sensors, such as accelerometers, because the former overcome some operational limitations related to contact sensor networks. The remote structural monitoring can, in fact, be performed without the need of accessing the structure to install wire sensors. This allows the investigation during emergency situations when monitoring activity can be required to ensure the safety of people, or when the target to be monitored cannot be directly accessible. The aim of this paper is the valuation of reliability of joint application of Ground-Based microwave Radar Interferometer technique (IBIS-S), High-Frequency Thermal Camera

(FLIR) and Ambient Noise Standard Spectral Ratio (NSSR) for the estimation of fundamental dynamic parameters of two reinforced concrete bridges. For Sihlhochstrasse Bridge (Zurich - Switzerland), the dynamic displacement data collected by the joint application of the FLIR thermal camera and the IBIS-S sensor were used to provide resonant frequencies and their evolution over time. For Musmeci bridge (Italy - Potenza), the dynamic parameters have been obtained by Ground-Based microwave Radar Interferometry and the consolidate techniques such as the Standard Spectral Ratio recording seismic ambient noise by velocimeters and accelerometers.

2. BASIC CONCEPTS OF METHODS

During the last years the IBIS-S (Image By Interferometric Survey of Structures) microwave radar interferometer was successfully applied for the monitoring of a wide variety of structures, such as tracking the vibration of bridges excited by vehicular traffic (Pieraccini et al., 2007, Gentile and Bernardini, 2008), the monitoring of the displacements of heritage architectural structures (Atzeni et al., 2010), for deflection measurements on vibrating stay cables (Gentile, 2010), and for in-field dynamic monitoring of engineering structures (Pieraccini et al., 2008, Rödelsperger et al., 2010). The main limitation of the sensor is that it provides the displacement along the radar's line of sight (LOS). This can be overcome by using simultaneously two systems orthogonal to each other or by placing the instrument in different positions. The IBIS-S microwave radar consists of a sensor module installed on a tripod with a 3D rotating head. The two horn antennas of the sensor module transmit the electromagnetic signals in the Ku frequency band of 16.75 ± 0.30 GHz, and receive the echoes from the targets to be processed in order to compute the displacement time-histories of different points of the investigated structure with a sensitivity of 0.01-0.02 mm. The maximum sampling frequency is 200 Hz. This innovative radar system, widely described in previous works (e.g., Gentile 2010, and references therein), is based on the Stepped-Frequency Continuous Wave (SF-CW) technique (Taylor 2001) and on the Differential Interferometric technique (Henderson and Lewis 1998). For each acquisition, the microwave radar measurements data were processed by using the commercial IBIS DATAVIEWER (IBISDV) software that gives the displacement time-histories evaluated from the IBIS-S radar sensor. For each measurement, the mean and the linear trends were removed from the signal, a 0.5 Hz high pass filtering and a cosine tapering with a damping of 20% and the derivative of the signal have been computed before applying the Fourier transform.
The thermal camera technology is a non-destructive diagnostic technique commonly used in different applications (Pascucci et al., 2008; Ha et al., 2012) mainly applied for the detection and characterization of defects in the structures' subsurface (Maierhofer et al., 2006) and for the displacement monitoring and verification of the structural integrity of buildings and structures (Proto et al., 2010). This type of analysis combined with other techniques is also used for the structural status monitoring and the application of vibration-based damage detection techniques (Doebling et al., 1996). The thermal imagery acquisitions were used to calculate the oscillation frequency of the monitored structure as derived from the difference between the structure temperature and the background temperature. The oscillation retrieval technique is based on the presence of pixels composed by both the monitored structure and the background. Such technique allows measuring the dynamic displacement of the structure orthogonal to the LOS by the use of the variation in time of the mixed pixels temperature in the investigated scene.
Actually a reliable possible alternative to characterize the dynamic behavior of civil structure is to perform ambient noise measurements by velocimeters and accelerometers analyzing with Ambient Noise Standard Spectra Ratio technique (NSSR). This technique is fast and non-destructive and can be applied to a large number of accessible points, as windows. The hypotheses at the basis of the method are generally satisfied: the amplification of the horizontal components of the motion is significant, especially for the out-of-plane component, whilst the amplification of the vertical component is negligible. When active mechanisms are present, the ambient noise SSR is expected to yield different spectral ratios for the different rigid bodies composing the mechanism. NSSR is obtained performing the ratio between the amplitudes of the Fourier spectrum of horizontal (longitudinal and transversal) components registered on the desk or on the shell and the same components registered on the soil (Parolai et al., 2005).

3. THE SIHLHOCHSTRASSE BRIDGE

The Sihlhochstrasse bridge (Figure 1A), located in Zurich on the motorway A3, is one of the largest bridges in Switzerland and is about 1.5 km (without ramps) long. It was completed in 1973 and major rehabilitation was carried out between 2000 and 2001. This is a reinforced concrete bridge equipped with girder boxes. Its deck has a width of 24.38 m and it is covered with asphalt pavement and a sealing between asphalt and concrete. In addition to the tendons in the girder boxes, there are also tendons orthogonal to the bridge axis in the bridge deck itself. There are concrete parapets on both sides and in the center of the bridge deck. The bridge is equipped with metal sound insulating walls. The main bridge is carried by pairs of concrete piles with oval cross section that are standing in the river Sihl (Figure 1B).

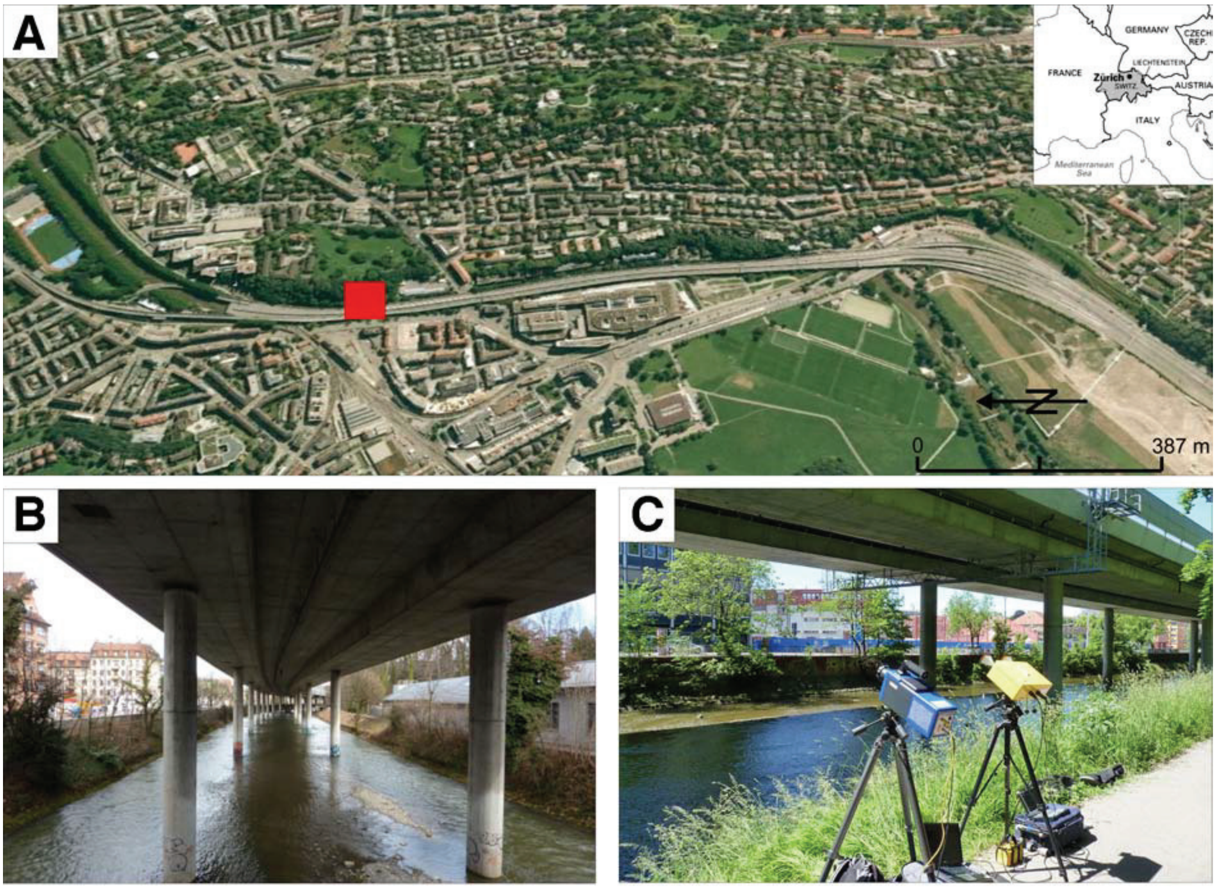

Figure 1. A) Sihlhochstrasse bridge test site: the red box highlights the location of measurements; B) piles in river Sihl; C) FLIR (on the left) and IBIS-S (on the right) sensors during acquisition.

3.1. Data acquisition and Results

For this test site the IRT camera was positioned close to the IBIS-S sensor to compare and analyze a different sensing technology for the structure vibration frequencies on the same target area (Figure 1C). The field measurement campaign was performed between 17 and 19 May 2011 on clear sky conditions. The measuring sessions were executed in different sets of measurements (about three for day) according to the heavy traffic loadings on the bridge. The IBIS-S system was placed in front of the Sihlhochstrasse Bridge at 15 m distance (Figure 1C) with a LOS angle $\theta = 30^\circ$, each IBIS-S acquisition had duration of about 20 minutes with a sampling frequency of 200 Hz.
Concerning the high sensitivity Thermal Infrared (TIR) instrumentation, we used a FLIR SC7900-VL thermal camera (LWIR; 7.7-11.5 μm). The FLIR camera has an integration range from 10 μs to 10 ms,

which incorporates a high quantic efficiency MCT focal plane array thus ensuring a very high radiometric resolution with a Noise Equivalent Temperature Difference (NEDT) < 25 mK. The frame rates are up to 6000 FPS (frames per second) in sub-windowing mode. The LWIR camera was applied by using the following configuration: a sub-windowing mode of 80x64 frames thus allowing 200 FPS and 150 µs of integration time, the FLIR camera was located on the ground installed on a tripod along a secondary pedestrian lane running parallel to the bridge in order to assure the covering of the area of interest of the bridge structure. The high frequency FLIR thermal acquisitions were performed at about 200 Hz. The camera has been pointed to a metal screw nut of higher temperature with respect to the concrete background and fixed to the structure to measure the oscillation frequency of the nut (Figure 2). High frequency thermal measurements were conducted for a period of 2 hours in order to observe different solicitations of the structure due to cars and trucks running on the bridge.

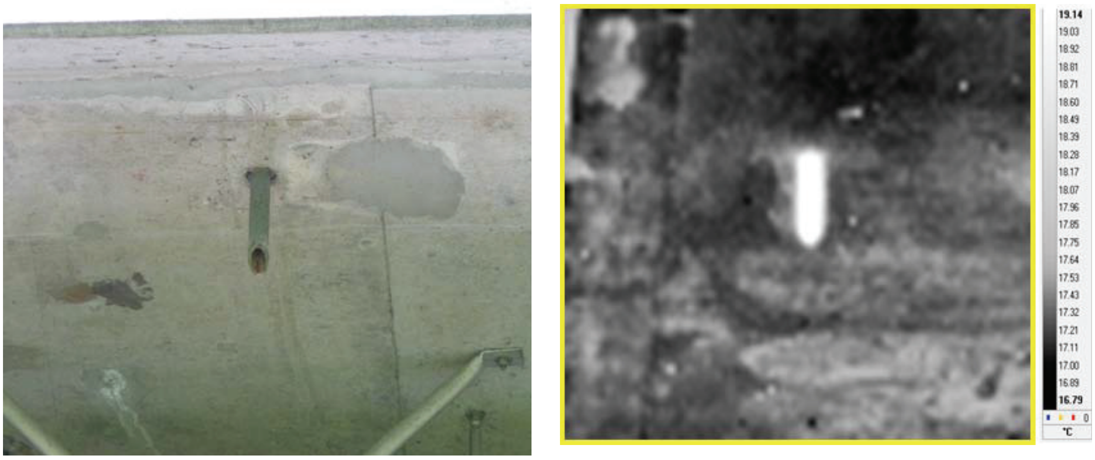

Figure 2. Left, example of a frame acquired by FLIR camera. The frame depicts a metal object (nut) solidly connected to the bridge structure that was used as a target to observe the thermal oscillation caused from the heavy vehicles traffic on the bridge. Right, the FLIR acquisition area used for calculating the oscillation frequencies.

In the Fourier spectrum of the IBIS-S acquisitions it is possible to observe a series of peaks from 0.3 to 8.0 Hz (Figure 3). Some frequencies are well recognizable in all acquisitions, while other frequency peaks are evident only for some acquisitions or have small amplitudes. Considering only the IBIS-S spectra it is very difficult to distinguish between the frequencies related to vertical movements and those related to the horizontal ones. This because the LOS angle was $\theta = 30^\circ$. In fact, the projection of the vertical oscillation of the bridge (which is the most important) along the LOS is one half of the nominal value and it cannot be considered negligible. On the other hand, since the bridge principally oscillates vertically, the few frequencies recorded by the FLIR thermal camera are surely related to the vertical oscillations of the bridge. A comparison between the spectra obtained by the IBIS-S system and FLIR camera allows discriminating the main frequencies related to the vertical and the horizontal oscillations (Figure 3). Table 1 summarizes the frequencies obtained by the two sensors: the frequencies at 0.3 Hz and 2.3 Hz are related to vertical oscillations, while the ones at 0.8 Hz, 3.2 Hz and 3.9 Hz are related to horizontal oscillations. It is important to bear in mind that one of the measured frequencies should be related to the site amplification. Further measurements should be carried out to assess the validity of the other frequencies, in particular those in the range 1.0-1.3 Hz, and 8.0-9.0 Hz that are observed by both the sensors without a stable common frequency value.

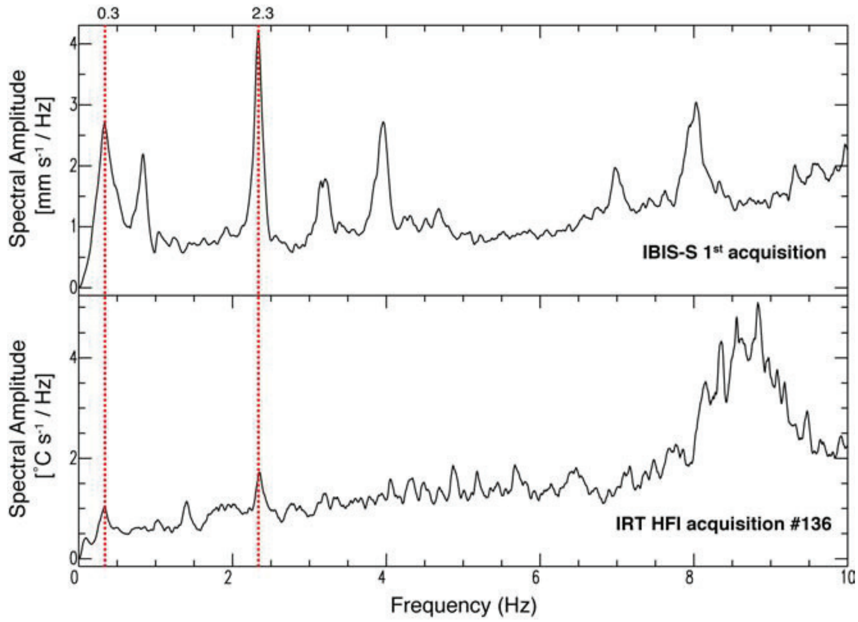

Figure 3. Comparison between the velocity Fourier spectrum obtained from the IBIS-S data (1st acquisition) and the Fourier spectrum obtained from the derivative of the FLIR camera data. Red dotted lines indicate the resonant frequencies commonly identified by both the sensors. These frequencies are related to purely vertical oscillations of the Sihlhochstrasse Bridge.

Table 1. Frequencies measured by the HFI thermal camera and the IBIS-S radar sensor. Frequencies that should be assessed by additional measurements are evidenced in grey.

Sensor	Measured frequencies (Hz)								
HFI thermal camera	0.3	-	1.0-1.3	2.3	-	-	-	-	8.7
IBIS-S radar sensor	0.3	0.8	1.0	2.3	3.2	3.9	4.2	7.0	8.0

4. THE MUSMECI BRIDGE

The Musmeci Bridge is a very considerable reinforced architectural concrete structure of the XX century, which was designed and built by the Italian architect Sergio Musmeci (1926-1981). One kilometre outside from the inhabited area of Potenza (Basilicata–Italy), the bridge represents an important flyover linking the city centre to the Potenza-Sicignano highway (Figure 4A). Then, it crosses the Basento river and a railway very close to the main train station of the city. Recently, the bridge shows several problems related to the aging and the intensive use due to the traffic load lately grown up and water infiltration phenomena. The bridge is constituted by an assembled reinforced box deck superimposed to a continuous reinforced concrete shell (Figure 4A1). The deck is composed by four 17.30 m span for a total length of the bridge equal to 69.20 m. The modular conception of the bridge made possible to focus the effort in terms of diagnostics and monitoring just towards the study of one span; the first span offered the undoubted benefit to exploit a large zone, usually used as car parking, in order to perform the mounting and dismantling sensors and equipments operations (Figure 4B).

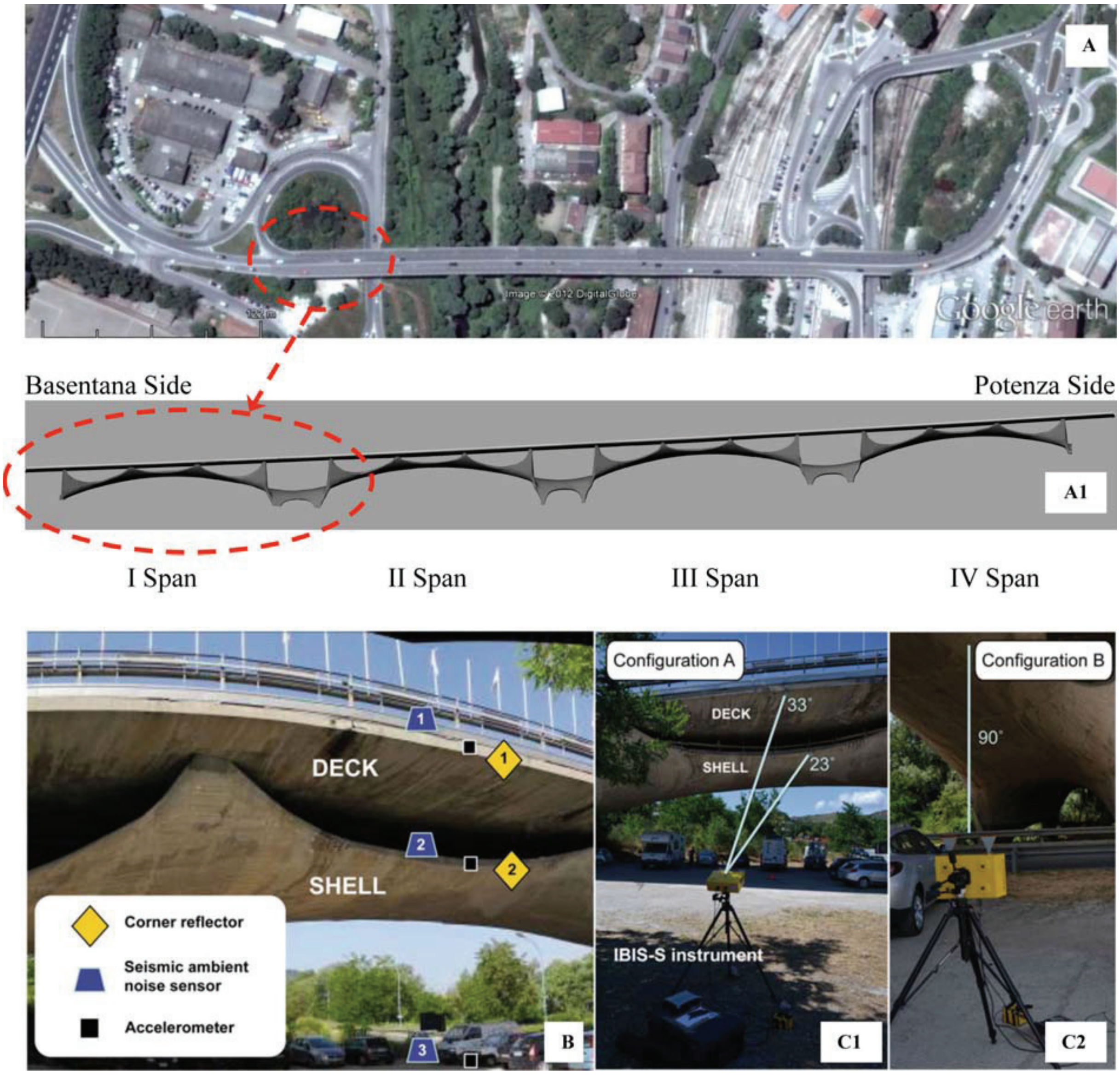

Figure 4: (A) Plan and (A1) sketch of the section of reinforced concrete Musmeci bridge; (B) Sensors installation at the Musmeci Bridge; (C1) Installation of the IBIS-S system in the configuration A; the sensor was placed in front of the bridge, illuminating the shell and the deck with LOS angles of 23˚ and 33˚, respectively. (C2) Installation of the IBIS-S system in the configuration B; the sensor was placed vertically under the bridge (LOS angle = 90˚).

4.1. Data acquisition and Results

Simultaneously radar and ambient noise measurements have been performed on Musmeci bridge on 18th, 19th and 20th July, the installation of sensors are reported in Figure 4B. Both the shell and the deck of the bridge were illuminated by the IBIS-S system at each acquisition. Furthermore, in order to improve the backscatter intensity of the structure, hence the quality of acquired data, two corner reflectors were installed on the deck and the shell of the bridge, respectively (Figures 4B and 4C1). We performed the dynamic survey of the structure by using different lines of sight (LOS) with the aim to decouple the horizontal displacement from the vertical one (Figures 4C1 and 4C2). Each acquisition had duration of about 20 minutes and we obtained a displacement signal with a sampling frequency of 200 Hz.

The following configurations were used:

- Configuration A: the IBIS-S system was placed in front of the Musmeci bridge in order to monitor the dynamic behaviour of the shell and the deck with LOS angles of 23˚ and 33˚ counterclockwise from to the horizontal axis, respectively (Figure 3C1);
- Configuration B: the IBIS-S system was placed under the Musmeci bridge (Figure 4C2) in order to monitor the vertical displacement of the shell and deck (LOS 90˚).

Joining to the radar measurements, two Tromino equipments were alternatively installed on the deck and on the shell and one permanently on the foundation soil to ambient noise measurements, each sampled 20 minutes of ambient noise at 128 Hz (Figure 4B). Moreover, six accelerometric stations were fixed on the bridge (deck and shell) and two stations on the soil as reference stations (as depicted in Figure 4B). Each station was linked to a central unit acquisition system equipped with a 24 bit digitizer. The sampling frequency ranges between 200Hz and 500Hz. On the soil only the horizontal components were monitored, on the contrary, for the bridge both horizontal and vertical components were examined.

We compared the Fourier spectra estimated by IBIS-S system with the Standard Spectra Ratio estimated by ambient noise recorded by velocimeter and accelerometer data. For all acquisitions we noted that displacements under traffic excitation were in phase for both the deck and the shell. During the data acquisition into the configuration B (the system was placed perpendicularly under the bridge), we observed that when a vertical load was applied to the bridge by the transit of a heavy vehicle, the maximum displacement of the deck was bigger than that observed for the shell by a factor of 2. The comparison of the Fourier spectra obtained by the IBIS-S radar sensor with those obtained by ambient noise SSR is reported in Figure 4. We observed in the Fourier spectrum two frequency peaks below 2 Hz and further four resonant frequency peaks in the range 2.6 – 3.7 Hz. All the frequencies were observed for both the deck and the shell of the bridge and with each technique. Peaks at frequencies below to 2 Hz were more evident in the IBIS-S spectra obtained for the configuration A (Figures 5A and 5C), while the others were more evident in the IBIS-S spectra obtained for the configuration B (Figures 5B and 5D). It worth noting that the fundamental frequency of the bridge (1.45 Hz), the second (1.85 Hz) and the fifth (3.7 Hz) eigenfrequencies are characteristic of transversal and vertical displacement components. The third and (3.0 Hz) the fourth (3.3 Hz) eigenfrequencies are characteristic of pure vertical displacements (Figure 4b and 4d). It is possible to suppose torsional modal shapes for the first, the second and the fifth eigenfrequencies, and bending modal shapes for the third and the fourth eigenfrequencies. The peak at 2.6 Hz is the soil resonance frequency estimated by ambient noise Horizontal-to-Vertical Spectral Ratio (HVSR) analysis (Nakamura, 1989; Gallipoli and Mucciarelli, 2001).

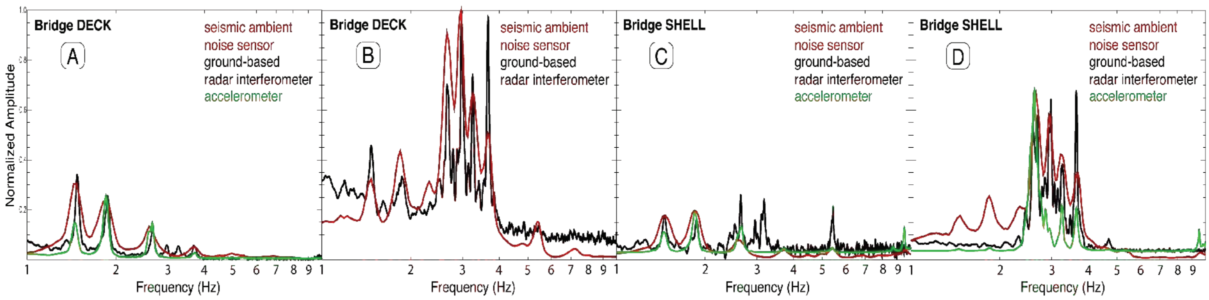

Figure 5: Comparison between the Fourier spectra obtained for the horizontal and vertical component of the deck (A, B) and the shell (C, D) oscillations of the Musmeci Bridge by using the three different sensors, in the frequency band 1 – 10 Hz. The ground-based radar interferometer results are indicated with a black line, while red lines and green lines represent those obtained by the seismic ambient noise sensor and the accelerometer, respectively.

5. CONCLUSIONS

We have presented the results about the joint application of remote sensing and in situ techniques in order to characterise the principal dynamic parameters of the Sihlhochstrasse (Switzerland) and

Musmeci (Italy) reinforced concrete bridges. The estimation of these parameters has been achieved by the joint application of microwave interferometry radar technology, high-frequency thermal camera and Ambient Noise Standard Spectral Ratio.
The comparison of the results obtained by the simultaneous application of such techniques on engineering structures shows an excellent agreement:

- to estimate dynamic parameters of the civil structure and cultural heritages (main vibrational modes in two orthogonal direction and relative damping, modal shape);
- to follow the dynamic parameters variation due to damage and structural degradation.

Moreover, the good agreement between the results obtained in this work, confirms the reliability of IBIS-S microwave radar sensor to provide displacement, main frequencies, and damping estimations, under the effect of natural excitation without any contact with the structure, for civil infrastructures.
This opens new perspectives in the monitoring of infrastructures. Indeed, it could be possible to make interferometric measurements of structures simultaneously with consolidated techniques, considering the first as a technique of reference in evaluating the dynamic parameters of the inaccessible points of the monitored structure. This approach could be suitable for the dynamic characterization of buildings that have been seriously damaged by an earthquake and/or structural degradation, for civil structures/infrastructures to overcome operational limitations and for cultural heritage buildings.

References

Atzeni, C., Bicci, A., Dei, D., Fratini, M. and Pieraccini, M. (2010). Remote survey of the leaning tower of Pisa by interferometric sensing. *IEEE Geo. Rem. Sens. Lett.* **7**,185–189.

Boutin, C. and Hans, S. (2008). How Far Ambient Noise Measurement May Help to Assess Building Vulnerability? *in Increasing Seismic Safety by Combining Engineering Technologies and Seismological Data*, M. Mucciarelli, M. Herak and J. Cassidy eds., Springer, 151-180.

Cader, D. S. (1936a). Observed vibration of buildings. *Bull. Seismol. Soc. Am.* **26:4**,245–267.

Cader, D. S. (1936b). Observed vibration of bridges. *Bull. Seismol. Soc. Am.* **26:4**,267–289.

Carden, E.P. and Fanning, P. (2004). Vibration based condition monitoring: A review. *Structural Health Monitoring* **3:4**,355-377

Çelebi, M., Phan, L. T. and Marshall, R. D. (1993). Dynamic characteristics of five tall buildings during strong and low-amplitude motions. *Struct. Des. Tall Build*. **2**,1–15.

Çelebi, M. and Liu, H. P. (1998). Before and after retrofit response of a building during ambient and strong motions. *J. Wind Eng. Ind. Aerodyn.* **77–78**,259–268.

Clinton, J. F., Bradford, S. C., Heaton, T. H. and Favela, J. (2006). The observed wander of the natural frequencies in a structure. *Bull. Seismol. Soc. Am.* **96**,237–257.

Chopra, A. K. (2007). Dynamics of structures: Theory and Applications to Earthquake Engineering, Third Ed., Prentice-Hall, New Jersey.

Doebling, S. W., Farrar, C. R., Prime, M. B. and Shevitz, D. (1996). Damage identification and health monitoring of structural and mechanical systems from changes in their vibration characteristics: a literature review. Report LA-13070-MS Los Alamos National Laboratory.

Dunand, F., Rodgers, J. E., Acosta, A. V., Salsman, M., Bard, P-Y. and Celebi, M. (2004). Ambient vibration and earthquake strong-motion data sets for selected USGS Extensively instrumented buildings. *U.S. Geol. Surv.* Open-File Report, 2004-1375.

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

Gentile, C. (2010). Application of Microwave Remote Sensing to Dynamic Testing of Stay-Cables. *Remote Sensing* **2**,36-51.

Ha, H., Han, S., and Lee, J. (2012). Fault detection on transmission lines using a microphone array and an infrared thermal imaging camera. *IEEE Trans. Instr. Measur.* **61**,267-75

Henderson, F.M. and Lewis, A.J. (1998). Manual of remote sensing. Principles and applications of imaging radar, John Wiley & Sons, New York.

Ivanovic, S. S., Trifunac, M. D. and Todorovska M. I. (2000). Ambient vibration tests of structures - A review. *ISET J. Earthq. Tech*. **37:4**,165–197.

Kohler, M. D., Davis, P. M. and Safak E. (2005). Earthquake and ambient vibration monitoring of the steel frame UCLA Factor building. *Earthq. Spectra* **21**,715–736.

Maierhofer, C., Arndt, R., Rollig, M., Rieck, C., Walther, A., Scheel, H. and Hillemeier, B. (2006). Application of impulse-thermography for non-destructive assessment of concrete structures. *Cem. & Concr. Compos.* **28**,393–401

Malone, R. M., Celeste, J. R., Celliers, P. M., Frogget, B. C., Guyton, R. L., Kaufman, M. I., Lee, T. L. and MacGowan, B. J. (2005). Combining a thermal-imaging diagnostic with an existing imaging VISAR diagnostic at the National Ignition Facility (NIF). *Int. Soc. Opt. Eng.* **5874**,1-8

Martire, G., Faggiano, B., Mazzolani, F.M., Zollo, A. and Stabile, T.A. (2010). Seismic analysis of a SFT solution for the Messina Strait crossing. *Procedia Engineering* **4**,303–310.

Mucciarelli, M. and Gallipoli, M.R. (2001). 10 years of Nakamura's technique: a review of theory, experiments and applications. *Bollettino di Geofisica Teorica ed Applicata* **42**,255-266.

Nakamura, Y. (1989). A method for dynamic characteristics estimation of subsurface using microtremor on the ground surface. *Quart. Rep. of Rail. Tech. Res. Inst.* **30:1**,25-33.

Parolai, S., Facke, A., Richwalski, S.M. and Stempniewski, L. (2005). Assessing the Vibrational Frequencies of the Holweide Hospital in the City of Cologne (Germany) by Means of Ambient Seismic Noise Analysis and FE modelling. *Natural Hazard* **34**,217-230.

Pascucci, S., Bassani, C., Palombo, A., Poscolieri, M. and Cavalli, R. (2008). Road asphalt pavements analysed by airborne thermal remote sensing: Preliminary results of the Venice highway. *Sensors* **8**,1278-96

Pieraccini, M., Parrini, F., Fratini, M., Atzeni, C., Spinelli, P. and Micheloni, M. (2007). Static and dynamic testing of bridges through microwave interferometry. *NDT&E Int.* **40**,208-214.

Pieraccini, M., Fratini, M., Parrini, F., Atzeni, C. and Bartoli, G. (2008). Interferometric radar vs. accelerometer for dynamic monitoring of large structures: An experimental comparison. *NDT&E Int.* **41**,258–264.

Picozzi, M., Milkereit, C., Zulfikar, C., Fleming, K., Ditommaso, R., Erdik, M., Zschau, J., Fischer, J., Safak, E., Özel, O. and Apaydin, N. (2010). Wireless technologies for the monitoring of strategic civil infrastructures: an ambient vibration test on the Fatih Sultan Mehmet Suspension Bridge in Istanbul, Turkey. *Bulletin of Earthquake Engineering* **8**,671-691.

Proto, M., Bavusi, M., Bernini, R., Bigagli, L., Bost, M., Bourquin, F., Cottineau, L. M., Cuomo, V., Vecchia P. D., Dolce, M., Dumoulin, J., Eppelbaum, L., Fornaro, G., Gustafsson, M., Hugenschmidt, J., Kaspersen, P., Kim H, Lapenna, V., Leggio, M., Loperte, A., Mazzetti, P., Moroni, C., Nativi, S., Nordebo, S., Pacini, F., Palombo, A., Pascucci, S., Perrone, A., Pignatti, S., Ponzo, F. C., Rizzo, E., Soldovieri, F. and Taillade, F. (2010). Transport infrastructure surveillance and monitoring by electromagnetic sensing: The ISTIMES project. *Sensors* **10**,10620-10639

Snieder, R. and Safak, E. (2006). Extracting the building response using seismic interferometry: Theory and application to the Millikan library in Pasadena, California. *Bull. Seismol. Soc. Am.* **96**,586–598.

Snieder, R., Hubbard, S., Haney, M., Bawden, G., Hatchell, P., Revil, A. and the Geophysical Monitoring Working Group (2007). Advanced non-invasive geophysical monitoring techniques. *Ann. Rev. of Earth Planet. Sci.* **35**,653–683.

Taylor, J.D. (2001). Ultra-wideband radar technology, CRC Press, New York.