RADAR-BASED MEASUREMENTS OF THE OSCILLATION PARAMETERS OF LARGE CIVIL ENGINEERING STRUCTURES

V. Gikas[a, *], S. Daskalakis[a]

[a] School of Rural and Surveying Engineering, National Technical University of Athens,
9 I. Polytechniou Str., Athens, Greece – vgikas@central.ntua.gr

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ABSTRACT:

This paper discusses the use of microwave radar interferometry for monitoring the dynamic behaviour of civil engineering works. It provides an overview of the method, its principles of operation and applications areas, with particular emphasis given on the IBIS-S system. Two case studies are considered and the results of the preliminary analyses are presented and discussed. The first case study involves the monitoring of the dynamic response of a tall chimney due to wind load. The second example examines the dynamic behaviour of a long cable-stayed bridge. In this case, the focus is placed on the effects that individual traffic events impose on the vibration response of the structure; particularly, along and on the midpoint of the main span of the bridge.

1. INTRODUCTION

Critical civil engineering infrastructures refer to fixed assets, which, if significantly damaged or destroyed would have serious disruption on the society and economy of an area or a country. Major transportation engineering systems such as highways and bridges, dams, and power plants form typical examples of critical infrastructure. Some usual causes being responsible for their damage or failure would refer to storms, floods, earthquakes or other effects. Therefore, one of the most important challenges in the field of civil engineering relates to development of structural health monitoring (SHM) programs (i.e. processes of implementing a damage detection, identification and adaptation strategy), able to provide critical information of unsafe conditions possibly occurring in a major technical work (Ansari, 2005).

Driven by progress in sensor technology, computer software and data processing capabilities, the deformation monitoring methods used in SHM programs have evolved rapidly over the last twenty years. Depending on infrastructure technical characteristics and the nature of the physical phenomena encountered, various types of sensors (electro-mechanical, optical, radar, etc.) or techniques (contact / non-contact, single / multiple points monitoring) can be used (Liu, 2010; Radulescu *et al*, 2010; Yigit *et al*, 2010; Erol, 2011; Moschas and Stiros, 2011). This paper is concerned with the use of microwave radar interferometry technique for measuring the oscillation parameters of large civil engineering structures. The key features of the method are introduced and preliminary results of the implementation of the method in selected technical works are presented and discussed.

2. MICROWAVE INTERFEROMETRY AND THE IBIS SYSTEM

Interferometry makes use of the principle of superposition to combine different electromagnetic waves, in a manner that the result of their combination has some meaningful property that is representational of the original state of the waves. In fact, when two waves of the same frequency combine, the resulting wave pattern is determined by the phase difference between the two waves. In effect, in the case of deformation monitoring, the phase difference relates to the displacement of an object in question (Hariharan, 2007).

Originally, the method was used to map terrain elevation movements of large areas by satellite with ground resolution of some meters (Sykioti *et al*, 2003). The same technique has recently applied in ground-based systems to measure the displacements of structures and physical processes. Depending on radar system technical specifications and setup configuration, displacements pertaining to low up to high dynamic phenomena can be retrieved. Based on measured displacements, the kinematic characteristics of a deforming structure or a physical process can then be computed to further assist in modal analysis studies.

The IBIS radar system was developed by IDS SpA and the University of Florence, and is commercially available in two configurations – a microwave interferometer (IBIS-S) and a ground-based synthetic radar aperture (IBIS-L) system (Gentile, 2009). IBIS-S configuration, which is of particular interest in this study, is capable of dynamic displacement measurements taken simultaneously at different points of a structure. Table 1 summarizes the technical characteristics of the system. A key feature of IBIS-S radar resides in its high displacement resolution regardless of the operational distance of the instrument. This is due to a special wave transmission technique, known as Stepped Frequency - Continuous Wave technique. According to this approach the radar sensor emits repeatedly a series of long duration electromagnetic waves by linearly increasing frequencies in discrete steps; and thus, the resulting waves have narrow instantaneous bandwidth (corresponding to individual pulses), while they retain a large effective bandwidth (Gentile, 2009; Rödelsperger, 2010). In a similar manner to satellite interferometry, IBIS-S can measure only radial displacements (i.e. movements in the sensor viewing direction). Therefore, in order to produce projected

* Corresponding author

displacements, the relative geometry between the sensor and the structure that defines the observation scenario should be resolved during field measurements. Also, in case that the kinematic behaviour of certain points are of particular interest, then special metallic targets need to be installed on the structure to ensure strong reflections from that points.

feature	value
transmission freq.	17.2 GHz (Ku-Band)
max. sampling freq.	200 Hz
min. range resolution	0.50 m
accuracy (actual displacement sensitivity)	0.01 mm - 0.1 mm
accuracy (based on electronic stability)	0.001 mm
max. obs. distance (dynamic mode)	500 m

Table 1. Technical characteristics of IBIS-S system

3. CASE STUDIES OF MEASURING THE OSCILLATION PARAMETERS OF STRUCTURES

3.1 Dynamic Monitoring of a Power Plant Chimney

In the first case study, experimental work was undertaken at the Lavrion Thermal Power Plant operated by the Public Power Corporation of Greece. The plant is located by the sea front in the SE Attiki region. The average annual wind speed in the area is 7 m/sec and a turbulence intensity of approximately 12%. Dynamic monitoring was undertaken at the tall (149 m) chimney of Unit I. Preliminary testing indicated that the best observation geometry between the sensor and the target is at a horizontal distance of 15 m and an elevation angle of 70 deg. Two datasets were collected at a recording frequency 100 Hz for approximately 30 min. The average wind speed during the experiments was about 13 m/sec.

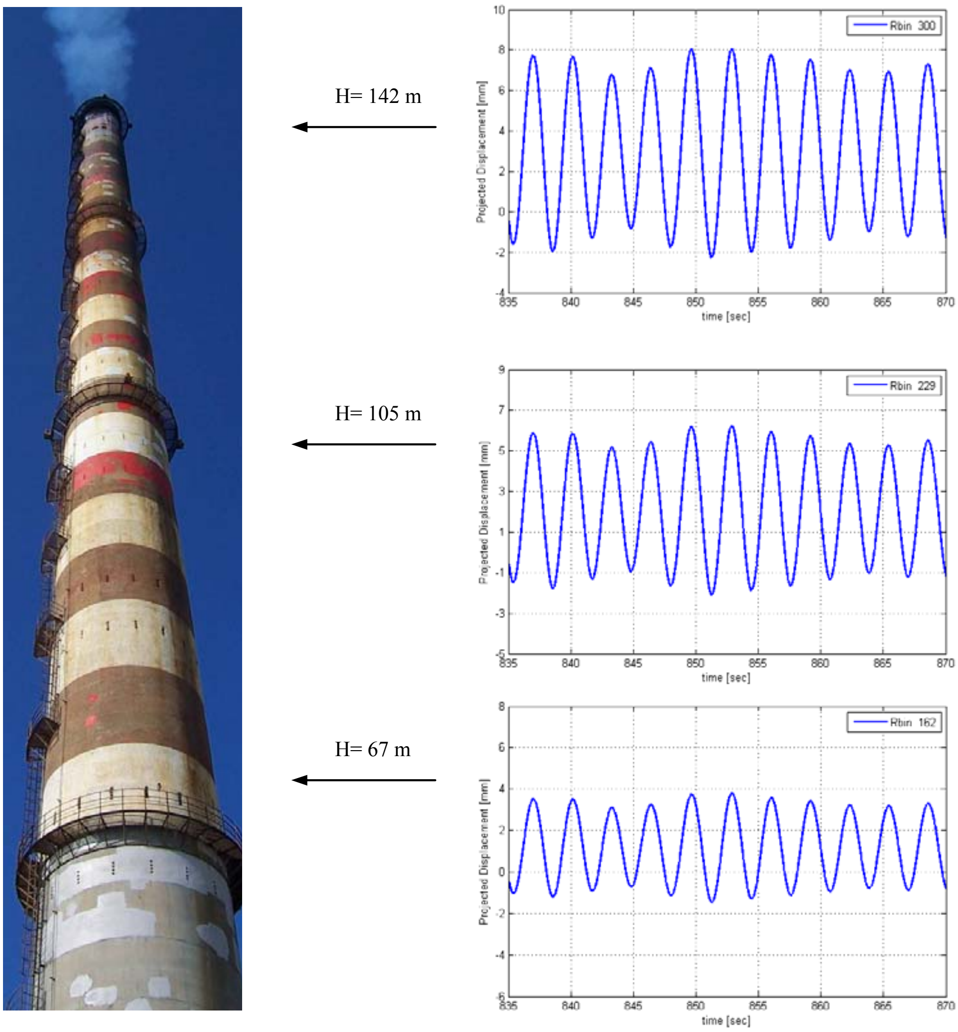

Figure 1. Horizontal displacements observed at three points at the upper half of the chimney for a 35 sec time period.

Data processing was accomplished in several steps. It involved generation of signal-to-noise ratio (SNR) plots (to identify and select highly reflective points), clutter removal (to accommodate for the effects of unwanted moving targets), and projection of the displacements measured in the direction of line of sight, into their horizontal equivalents. In this case, due to the elongated observation geometry, displacement projection computations were relied on a total station survey (Androulaki, 2011).

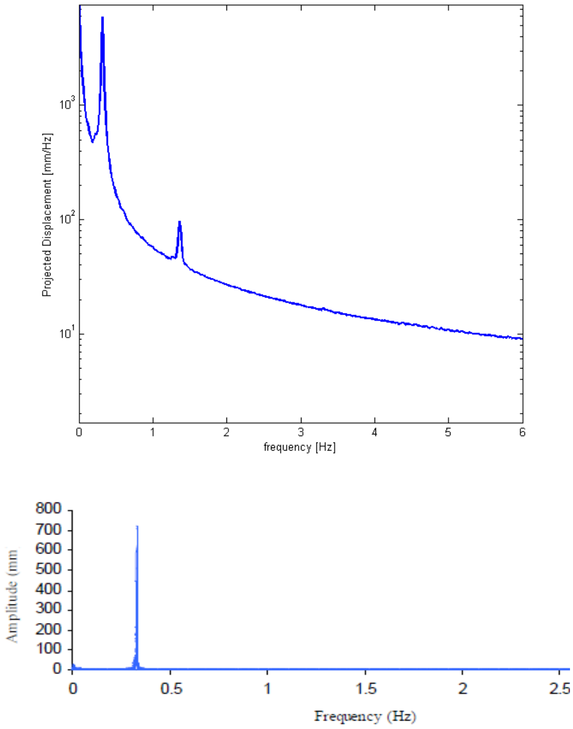

Figure 2. Microwave radar (top) and robotic total station (bottom) spectra computed for the top of the chimney.

Figure 1 contains the projected displacements measured at three equidistant points situated at the upper half of the structure. In order to clearly expose the periodic pattern of motion, a relatively short (35 sec) time interval is only displayed. As expected, from these plots is immediately evident the similarity in the pattern of motion. Also, an increase in displacement amplitude is observed from the bottom to the top of the structure. Figure 2 shows the dynamic behaviour of the structure in the frequency domain. From the top diagram the dominant oscillation frequency at the top of the structure is evident and equals 0.320 Hz. Secondary oscillation frequencies are also revealed – however, with the exemption of the frequency component at 1.35 Hz, these are hard to visualize due to their significantly lower power. As expected, analysis in different heights concluded in similar results.

In the past, the same structure was observed using a robotic total station system (RTS) and on-purpose designed software that facilitates recording the polar coordinates of a topographic prism with a recording frequency up to 6 Hz and internal clock time stamping of 0.001 sec (Gikas, 2008; Maritsoudis, 2008). For this purpose, a cyclic prism was mounted on the top of the chimney and a number of experiments were undertaken under similar weather conditions to those encountered in this study. Interestingly, the dominant oscillation frequency computed from the RTS tests (0.327 Hz – see Figure 2, bottom) is practically identical to the value computed using the radar system – suggesting that the results obtained from the two methods are correct. However, the RTS method suffers a low recording frequency and is restricted to a single point monitoring. Therefore, using an RTS it would be impossible to compute secondary frequencies and to obtain the mode shape (i.e. the variation of amplitude oscillation with height for a certain frequency) of the structure.

3.2 Dynamic Monitoring of a Cable-Stayed Bridge

The second case study discusses the results obtained from a number of experiments undertaken at Evripos cable-stayed bridge in Greece. This paper does not attempt a comprehensive deformation monitoring analysis of the bridge; it rather concentrates on a preliminary investigation of the dynamic response of the bridge deck and the pylons caused by vehicular traffic. In particular, the focus is on the displacement time-histories and oscillation frequencies obtained from microwave interferometry data, associated with individual heavy vehicle traffic events (Yang *et al*, 2004; Gikas *et al*, 2011).

Evripos cable-stayed bridge is located in Central Greece and serves as a link between the mainland of Greece and the island of Evia (Figure 3). The bridge, which stands 40 m above sea level, has opened to the public in 1993 and since then has undergone through regular maintenance programs. It has a total length of 695 m, comprised of a 215 m long main span, two side spans of 90 m each, and eight access parts of a total length 299 m. At both ends of the arch, stands a pair of 90 m high pylons, from which, are suspended 72 cables.

Figure 3. Evripos cable-stayed bridge

Figure 4. IBIS-S system setup. The triangles in yellow denote the area of observation (left), whereas, the circle denotes the location of the instrument by the basement of the pylons (right).

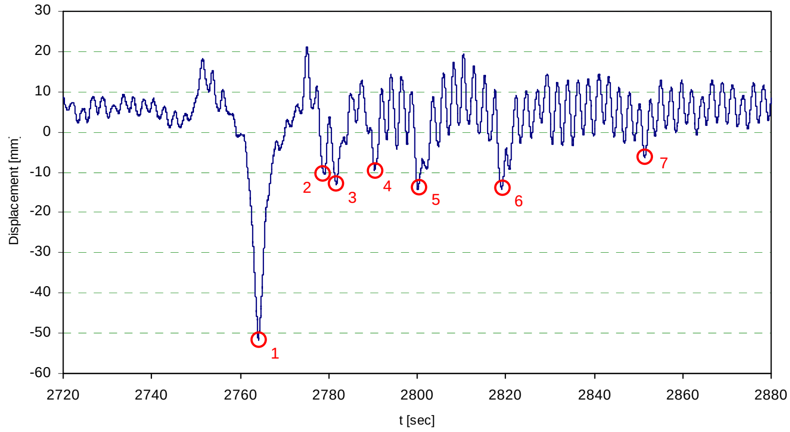

Figure 5. Vertical displacements observed at the main span midpoint for total period of 160 sec. The events shown in circles correspond to individual heavy vehicle (buses, trucks and very heavy trucks) crossing the bridge.

Figure 6. Snapshot pictures taken from the video camera recordings that correspond to events 1, 4 and 6 of Figure 5.

In order to study the dynamic response of the deck, the radar sensor was setup next to the basement of the pylons lying on Evia side, facing the deck from underneath (Figure 4). A dataset of 84 min of continuous observations was recorded, so that, a large number of heavy vehicles crossing the bridge was guaranteed. Also, the deck was video recorded during data acquisition to allow identification and matching of measured displacements to individual traffic events.

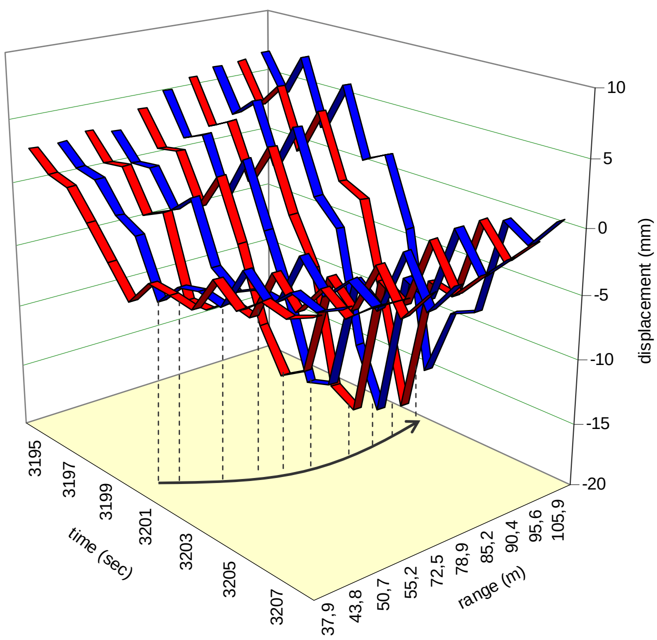

Figure 7. Vertical displacements measured for a section of the bridge deck that corresponds to range interval 38 m - 105 m (measured from the inner edge of the pylons lying on Evia side; Rbins 48-111, see also Figure 4 left) for a period of 13 sec. During this time only one heavy vehicle crosses the bridge. The maximum vertical displacement (d=-17 mm) is observed about the middle of the central span.

Figure 5 shows the vertical displacements obtained in the middle of the central span of the bridge for a time period of 160 sec. This diagram reveals that the bridge is in continuous vibration. Also, is clearly evident a number of peak displacements (denoted in circles) that appear to be associated with individual traffic events. In fact, these results can be explained by examining this diagram in combination with the video camera recordings. Cross-examination of the measured displacements against the video camera pictures reveals a direct correspondence between the time of peak displacements and the time of heavy vehicles crossing the bridge. As an example, the pick displacements denoted by circles 1, 4 and 6 correspond to the snapshots depicted in Figure 6. Furthermore, it can be concluded that the magnitude of displacements matches the type of vehicles crossing the bridge – i.e. the larger displacements correspond to heavier vehicles.

Figure 7 shows the evolution of vertical displacements along a section of the bridge deck for a short (13 sec) period of time, which corresponds, to the time it takes a heavy truck vehicle to travel along the mid span of the bridge. From this plot a number of conclusions can be drawn. The most important, however is, that the displacements appear to increase gradually as the vehicle travels along the bridge and reach their maximum about the middle of the deck for the time the truck passes over this area. Of course the general trends of these estimates could have been predicted from common sense. The advantage of this approach is that they can be quantified so that they can be directly compared with design specifications for quality control purposes. Having said that, it should be noted that observations were taken under normal operating conditions of the bridge; and thus, the displacements reported here, reflect the combined impact of the heavy truck and passenger vehicle traffic. Also, because of the type of material encountered and the lack of sharp edges on the structure, the signal reflections obtained are not always as strong as needed to produce high quality data for any observation distance desired. A more comprehensive study of the bridge should include the installation of reflective targets along the deck and a temporary stoppage of traffic to carry out specifically designed dynamic analysis tests.

Finally, for the same observation scenario, the frequency analysis of the bridge was obtained from the processing of all available observations. Figure 8 shows the radar spectra obtained for the midpoint of the main span. From this diagram is evident that two oscillation frequencies are prevailing – i.e., f_1= 0.433 Hz and f_2= 0.833 Hz. Previous studies (Lekidis *et al*, 2005) using GPS observations have indicated for the same structure a dominant frequency close to 0.5 Hz, whereas, robotic total station surveys resulted in a dominant oscillation frequency of 0.56 Hz. Clearly, further analysis of the radar data and cross-comparisons with the results of other monitoring methods and FEM analyses would enhance the findings concerning the dynamic behaviour of the structure.

4. CONCLUSIONS

This paper deals with the dynamic monitoring of structures using microwave interferometry, and in particular IBIS-S system. Two case studies are considered: (a) monitoring the dynamic response of a tall chimney against wind load, and (b) monitoring the dynamic behaviour of the deck of a long cable-stayed bridge as a result of vehicular traffic. Data analysis confirmed the suitability, reliability and robustness of IBIS-S system, and revealed its potential and limitations against other deformation monitoring methods. Furthermore, useful conclusions that relate to the dynamic displacements and oscillation frequencies of the two structures were drawn.

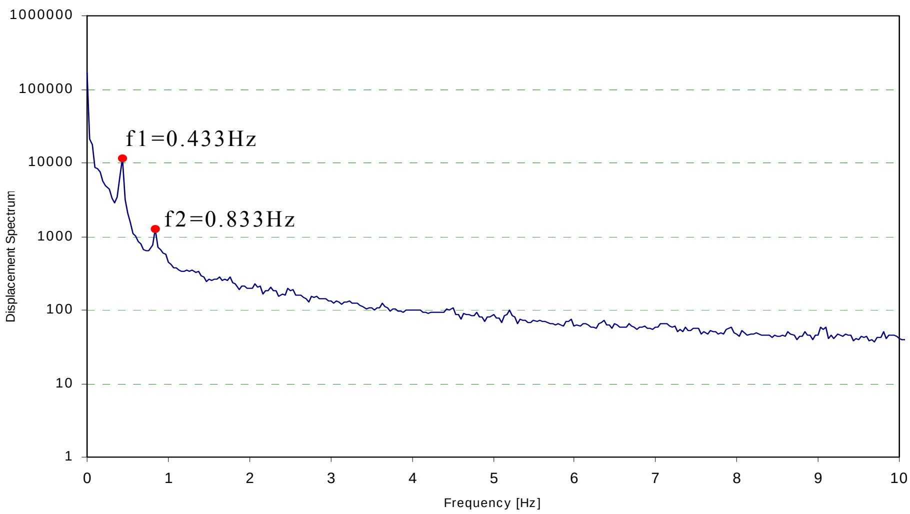

Figure 8. Frequency response computed for the midpoint of the main span of the bridge.

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