Deck and Cable Dynamic Testing of a Single-Span Bridge Using Radar Interferometry and Videometry Measurements

G. Piniotis, V. Gikas, A. Mpimis, H. Perakis
School of Rural and Surveying Engineering,
National Technical University of Athens, 9 Iroon Polytechniou Street, Zografou, Athens, Greece, 15780

Abstract. This paper presents the dynamic testing of a roadway, single-span, cable-stayed bridge for a sequence of static load and ambient vibration monitoring scenarios. Deck movements were captured along both sideways direction of the bridge using a Digital Image Correlation (DIC) and a Ground-based Microwave Interfererometer (GBMI) system. Cable vibrations were measured at a single point location on each of the six cables using the GBMI technique.

Dynamic testing involves three types of analyses; firstly, vibration analysis and modal parameter estimation (i.e., natural frequencies and modal shapes) of the deck using the combined DIC and GBMI measurements. Secondly, dynamic testing of the cables is performed through vibration analysis and experimental computation of their tension forces. Thirdly, the mechanism of cable-deck dynamic interaction is studied through their Power Spectra Density (PSD) and the Short Time Fourier Transform (STFT) analyses. Thereby, the global (deck and cable) and local (either deck or cable) bridge modes are identified, serving a concrete benchmark of the current state of the bridge for studying the evolution of its structural performance in the future. The level of synergy and complementarity between the GBMI and DIC techniques for bridge monitoring is also examined and assessed.

Keywords. radar interferometry, image correlation, vibration monitoring, cable-stay bridge

1 Introduction

Nowadays, continuous Structural Health Monitoring (SHM) programs using a permanent dense sensor array are generally motivated for large, long-span bridges, as these structures experience extreme loads usually caused by earthquakes, excessive winds and ice effects on the cables (Brownjohn et al (2010), Koh et. al. (2011), Yi et al. (2014)). In contrast, for the case of small-sized, short-span bridges, condition assessment studies are usually employed in the form of measurement campaigns for the confirmation of design, the calibration of numerical modeling and overly for structural integrity verification as a means for safe operating conditions and maintenance planning (Gikas et al. (2014)). In order to ensure cost-effectiveness in the monitoring operations, such condition assessment exercises are performed periodically and in conjunction with traditional inspection audits realized in the form of static load tests and dynamic testing scenarios. The first category aims at verifying the structural integrity of a bridge through FEM (Finite Element Model) updating, whereas the latter intends at computing its real dynamic properties, including the natural frequencies, the modal shapes and damping factors of the structure.

Today, with only a few exemptions found in the literature (Brincker et al. (2010)), Ambient Vibration Testing (AVT) is the standard dynamic testing procedure used for the assessment of dynamic parameters of bridges and for system identification. This approach relies on vibration measurements undertaken at critical locations on a bridge under ambient loading. At an analysis stage, the computation of bridge dynamic properties relies on alternative output-only modal identification techniques, either parametric or non-parametric ones, all of which assume a white noise excitation input (Hoa et al. (2010), Kaloop et al. (2015), Kaloop and Hu (2015)). The most widely used measurement technique for bridge AVT employs high sensitivity accelerometers or fibre-optic sensors which are deployed suitably at strategic locations on the structure. However, despite their proven reliability, these techniques can be difficult and time-consuming to implement, whereas direct contact with the structure is required (Moschas and Stiros (2015)).

peer reviewed JISDM 2016 Vienna

This study focuses on the use of the GBMI and DIC technologies for dynamic bridge testing. Based on their individual characteristics, GBMI and DIC techniques are used in a complementary way for the dynamic testing of the main structural elements of a short length, single-span, cable-stayed bridge. Particularly, vibration analysis and modal identification of the deck is performed using the GBMI and DIC observations obtained at neighboring locations on the bridge deck. Cable vibration analysis and deck-cable interaction analysis relies solely on GBMI measurements. Finally, in order to evaluate the global integrity and structural safety of the bridge, an experimental assessment of cable tensions is performed based on the GBMI measurements.

2 Monitoring Techniques and Instrumentation

2.1 GBMI and DIC monitoring techniques

The GBMI and DIC sensing techniques are relatively new approaches used for the dynamic monitoring of civil engineering structures. They rely both on discrete point displacement measurements. However, they employ a completely different working principle and are characterized by different error sources; and therefore, can be used in a synergetic as well as corroborative way.

The GBMI observation technique employs the interferometric principle. The method relies on the computation of scattering object displacements using the phase information obtained by a microwave radar sensor from repeated electromagnetic pulse transmissions (Gikas (2012), Pieraccini (2013), Gentile (2010), Kuras et al. (2014)). Based on measured displacements, the kinematic characteristics of a deforming structure can be computed for use in dynamic and modal analysis studies. The method facilitates a high recording rate and displacement accuracy as well as long operational distances. However, the most significant drawback of the GBMI method relates to the radial principle of operation that facilitates movements only in the sensor viewing direction, resulting in a one-dimensional image of the observed scenario, which makes difficult to resolve the torsional modes of a bridge deck.

Conversely, the DIC technique can resolve two- or even three-dimensional point movements on a structure depending on the number of cameras used and their geometry setup. The working principle of the DIC technique relies on the analysis of the optical flow of camera images observing an illuminated scenario using digital image correlation techniques (Caetano et. al. (2011), Choi et. al. (2011)). The most widely-used method is the feature-based optical method that monitors characteristic features on a structure (e.g. point features realized by edges, corners or structural discontinuities) and tracks their displacements from frame to frame (Morlier et al. (2007)). Other approaches rely on the study of image intensity variation using a dense velocity field from an image sequence (Morlier et al. (2007)). This technique, despite its ability to provide high quality displacements on the image sequence, their conversion to actual displacements on the structure is not always a straightforward procedure. Moreover, the DIC technique is an optical method, and therefore, is prone to atmospheric effects especially for long operating distances, whereas changes in the image scene (e.g. cloudy versus a clear sky background) would affect measurement stability. Finally, the method necessitates high precision topographic measurements for establishing the setup geometry between the cameras and the structure observed.

2.2 Sensor specifications

In this study, the IBIS-S (IDS Sp.A.) GBMI system was used. It consists of the radar module, a control PC and a power supply unit. A key feature of the IBIS-S system is the high displacement resolution obtained at any observation distance within its range of operation. This is due to the wave transmission technique employed in the system, known as Stepped Frequency Continuous Wave (SF-CW) technique (Gikas (2012)). The radar sensor emits repeatedly a series of long duration electromagnetic waves by linearly increasing frequencies in discrete steps. Therefore, the resulting waves have a narrow instantaneous bandwidth while they retain a large effective bandwidth. IBIS-S system features a maximum operating range of 500 m and accuracy in displacement measurement of the order of 0.1 mm or better (Pieraccini (2013)).

Regarding the videometry technique, this study employed the Video Gauge system produced by iMETRUM Ltd. Its working principle relies on pattern recognition and sub-pixel interpolation techniques applied sequentially on video recorded images that allow a resolution better than 1/100.000 of the visible area (Waterfall et al. (2012)). In this work a dual camera setup was used to produce two-dimensional displacements in the vertical plane for a number of specifically designed ring type, paper-made targets, fixed on the bridge deck, the pylon and the cables. Original displacements were computed on the digital images in pixels. In order to convert measured displacements from pixels to real units a conversion factor was calculated using a known distance between two points both in the image and in the real world.

3 The Bridge, the Load Testing Program and Field Work

3.1 Description of the Bridge

The test bridge, named Pallini bridge, is a roadway, single-span, cable-stayed bridge located in the greater area of Athens, Greece and operated by Attikes Diadromes S.A. The bridge consists of a 55.5 m long steel-composite deck suspended by six cables which are anchored from two Λ-shaped pylons as shown in Figure 1. The deck width varies between 13.4 m and 18.5 m. The pylons are 18.5 m tall, they are connected at the top-end, whereas their stressed and distressed elements are made of prestressed concrete and steel respectively.

3.2 Static load and ambient vibration testing

In order to assess the structural integrity of Pallini cable-stayed bridge a series of static load and ambient vibration tests took place in conjunction with a visual inspection program, nearly ten years after its completion and commissioning. Static load testing was undertaken in order to assess the actual condition of the bridge against the assumptions made in the finite element model. For this purpose a pre-weighted, three-axle truck vehicle was used to serve as a static load applied at predefined deck locations. In order to maximize cable tensions, truck locations were realized at the six cable anchor points as shown in Figure 1.

In order to estimate the dynamic behavior of the bridge, AVT was undertaken with an empty bridge using Operational Modal Analysis (OMA) (Gikas et al (2014b), Gikas et al. (2014c)). This article concentrates on the dynamic tests, particularly the deck and cable behavior and on their dynamic interaction.

3.3 Data acquisition

In order to eliminate the atmospheric effects on the raw observables data acquisition took place during night hours and in dead calm wind conditions, whereas observation sessions were scheduled to last short time intervals. In addition to the GBMI and DIC systems discussed already, deck displacements were captured for the static tests using precise levelling and a digital inclinometer sensor array. During the dynamic tests, which are of particular interest in this study, deck movements were observed along both sideways of the bridge deck using the DIC system and by the cable anchor point locations on the deck using the GBMI technique (Fig. 2). Cable vibrations were measured at a single point location, at each one of the six cables using the GBMI system. Specifically, cable vibrations were measured perpendicular to the cable axis at about 1/3 of the distance measured from the cable anchor point at the top of the pylons.

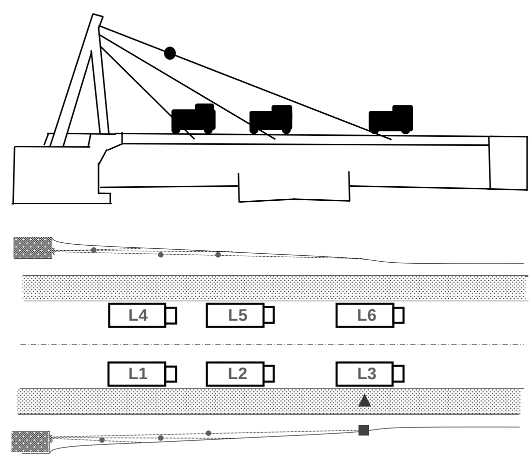

Fig 1. Truck locations during the static load tests. GBMI and DIC data presented in Figure 3 refer to deck locations marked in square and triangle, respectively. GBMI cable data refer to point location marked in circle.

4. Deck and Stay-cable Vibration Analysis

4.1 Deck vibration analysis

Vibration analysis provides a first indication of the dynamic behavior of Pallini bridge through studying its motion and spectra frequency characteristics. Figure 3 shows a subset time-series extraction of the deck settlements obtained by the long cable anchor point using the GBMI (up) and DIC (down) systems. Both systems indicate a similar average vibration displacement value of the order of ±0.3 mm with small (< 0.01 mm) differences in their mean values. From these plots is also evident the periodicity of motion.

Fig. 2 GBMI corner targets fixed by the cable anchor points (up), and DIC ring-type targets placed along each sidewalk of the bridge (down).

More specifically, the dominant period is apparent, whereas the variability in the long period displacement pattern is attributed to the deck bumping response resulting from small-size, short-term variations in the wind intensity.

Analysis obtained in the frequency domain for a subset of measured displacements under ambient loading results to the Power Spectral Density (PSD) plots shown in Figure 4. The first thing to note from these plots is that the GBMI and DIC systems exhibit similar peak values. This independent check verifies the performance of both systems and validates the correctness of the results obtained.

Regarding the actual performance of the structure, the FFT analysis shown in Figure 4 reveals the dominant vibration frequencies of the deck; however, a complete characterization of its dynamic properties is discussed in Section 5.

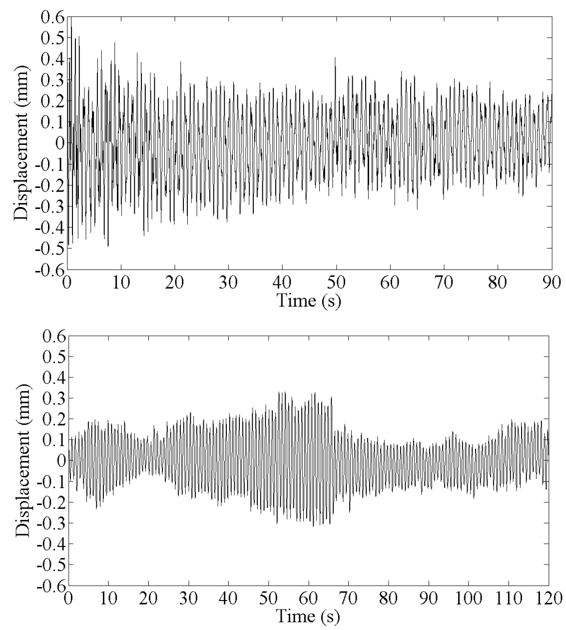

Fig. 3 Subset of deck settlement time-series observed using the GBMI (up) and DIC (down) systems by the long cable anchor point under ambient loading.

4.2 Stay-cable vibration analysis

Cable vibration analysis is confined only on the GBMI vibration measurements obtained at a single point location on each of the six cables. Specifically, the top plot of Figure 5 shows the displacement time-series obtained for a data subset for the long cable recorded under ambient vibration loading. In this plot a superimposition of signal components is evident with dynamic displacements of a maximum value of about ±0.1 mm.

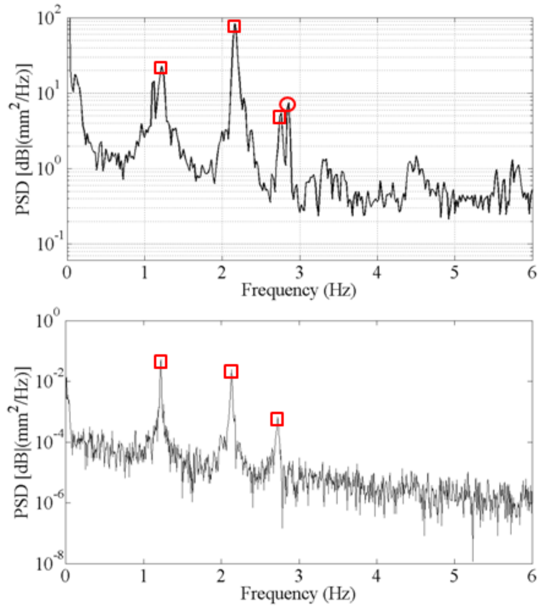

Fig. 4 PSD of the deck obtained by the long cable anchor point using the GBMI (up) and DIC (down) techniques under vibration loading.

The bottom plot of Figure 5 shows the corresponding PSD diagram obtained for a subset of displacement observations. Again, a number of peaks is clearly evident in this plot; however, a qualitative interpretation of their origin is attempted in Section 5.2, after a deck modal analysis is completed.

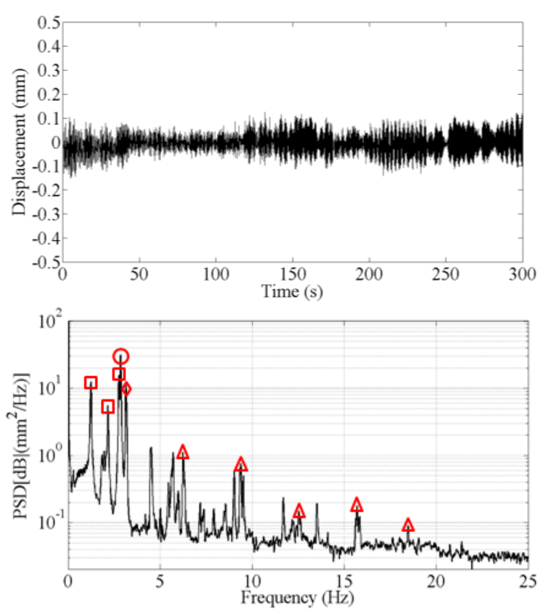

Fig. 5 Long cable time-series displacements (up) and PSD (down) obtained under vibration loading.

5. Deck and Stay-Cable Dynamic Analysis

5.1 Deck modal analysis

The Frequency Domain Decomposition (FDD) method was used to perform a modal analysis study of the bridge deck. The method is realized through performing a Singular Value Decomposition (SVD) operation to the PSD matrix of measurements (Brincker et al. (2000)). This operation produces the PSDs of a set of Single Degree of Freedom (SDOF) systems. Therefore, using the SDOF equations it is possible to estimate the modal frequencies of a structure via peak-picking on the singular values diagram. However, contrary to the standard Peak-Picking (P-P) method, the FDD technique assumes that frequency picking is performed on the singular values, and therefore, FDD is capable of successfully resolving close-spaced modes, which is common for complex structures including bridges.

In this work, in order to obtain a complete as possible picture of the deck modal properties, vibration measurements were obtained simultaneously at point locations running along both sideways of the deck (Fig. 1). Particularly, a dual camera setup was employed so that, each camera recorded the dynamic settlements at five target points, placed alongside each of the sidewalks of the deck. Therefore, the simultaneous video recordings of all DIC targets facilitated the required data to compute the bending as well as the torsional modes of the bridge.

Figure 6 shows the singular values of the PSD matrix of the deck's response obtained using the complete DIC dataset. Also, the dominant frequencies which correspond to the three principal modes of the deck (marked in red squares) are shown up in the same plot. Figure 7 shows the resulting mode shapes of the deck.

5.2 Deck and stay-cable interaction

Based on the findings of modal analysis results discussed in Section 5.1, a more comprehensive dynamic analysis of the bridge elements is possible. Specifically, as shown in Figure 4, examination of the PSD plot of the deck reveals clearly its three dominant modes; specifically, 1.24, 2.16 and 2.76 Hz). Evidently, these findings are in agreement with the modal analysis results shown in Figure 7. As expected, the picks found in Figure 4 are also apparent in the PSD plot of the cables, shown in squares in the bottom plot of Figure 5, indicating the effects of deck dynamics on the cables. A more detailed examination of the PSD plot of the deck reveals a peak at 2.86 Hz, which also appears on the cable spectra (marked in both cases in circles), suggesting a global frequency effect between the two bridge elements.

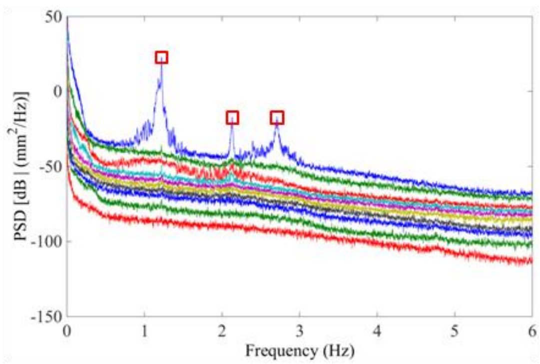

Fig. 6 Singular values of the PSD matrix of the frequency response of the deck computed using the DIC data.

Finally, a peak at 3.14 Hz (shown in diamond) is evident in the cable PSD plot (Figure 5, bottom plot), which is attributed to the first modal frequency of the cable. In fact, the same plot exhibits peaks at almost integer multiples (shown in triangles) of this fundamental frequency value supporting the argument that the peak value at 3.14 Hz corresponds to the first mode of the cable.

In order to further examine the hypothesis regarding the global and local character of peaks observed at 2.86 Hz and 3.14 Hz, the Short Time Fourier Transform (STFT) diagram is constructed for the long cable vibration data. The STFT diagram is a time-frequency spectrum that is capable to capture changes in the spectral characteristics of a signal over time. Its construction assumes the implementation of the Fourier transform to a set of data in a repeatedly manner, as this window slides through the entire record. Figure 8 shows the STFT plot derived for the complete time history of the static trials as the test truck moves gradually from location L1 through location L6 (Fig. 1). From the STFT plot is evident that peak 2.86 Hz is uniformly stimulated irrespectively of the truck location on the deck suggesting its global character. Contrary, the stimulation of the peak value 3.14 Hz is clearly associated with the truck location providing a strong argument of its local character. As shown in Figure 8 this becomes more apparent at the time instants the truck brakes and stops by the anchor point of the long cable (L3 load scenario).

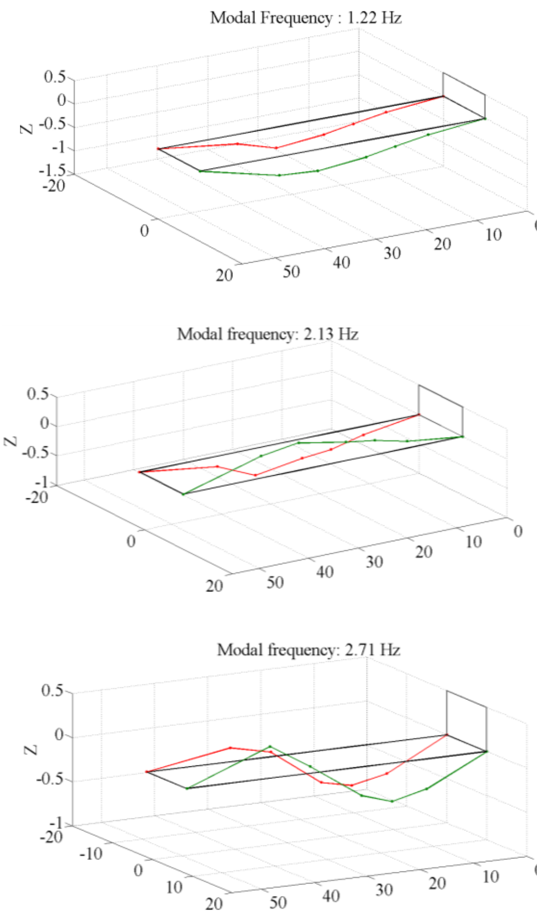

Fig. 7 Modal shapes of the bridge deck computed using the DIC data.

6. Evaluation of stay-cables tensions

Previous studies (Gentile (2010)) have demonstrated that in many cases microwave interferometry can serve as a simple, accurate and safe technique for evaluating the structural integrity of bridge stay-cables. In this study, in order to evaluate the actual tensions applied on the stay-cables a set of GBMI vibration measurements were acquired and analyzed as follows. At first, the stay-cables were measured under operational load conditions (i.e., wind and traffic effects), followed by capturing a dataset during static loading, in which case the truck was stationary by the long cable anchor point. The top and bottom plots of Figure 9 show the PSDs of the long cable response computed for the ambient load

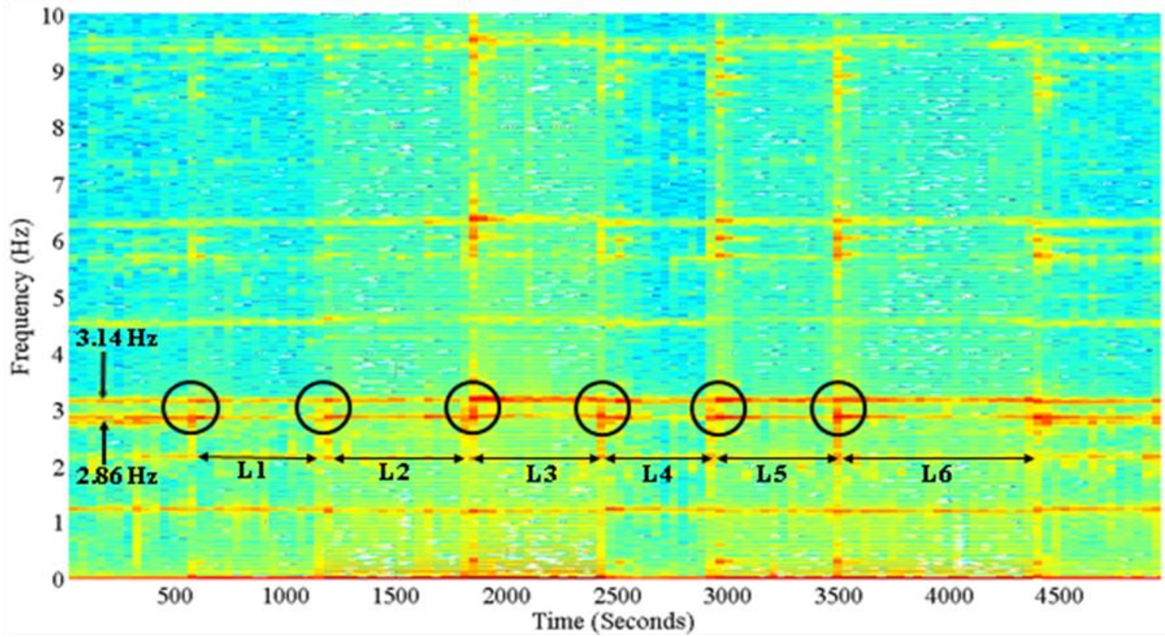

Fig. 8 STFT diagram computed from the GBMI data acquired by the long cable anchor point during the truck load tests.

and static cases respectively. In these plots the cable modal frequencies are marked with triangles.

Evidently, a thorough examination of the PSD plots, indicates a linear correlation between the mode order and the corresponding cable frequency, suggesting that the taut string model equation (Gentile (2010)) can be applied as follows.

$$T = 4\rho L^2 (\frac{f_n}{n})^2 \qquad (1)$$

In Equation (1), ρ is the mass per unit length and L is the effective length of the cable. The taut string model was applied for the long cable resulting in tension values of 4516 KN and 4682 KN for the ambient and static load cases respectively. In effect, the tension values computed from this analysis constitute base information that can be used as a benchmark, against which the results of future monitoring condition campaigns may be compared to assess the evolution of structural integrity of the bridge cables in time.

7. Conclusions

This paper presents summary results obtained from the combined use of the GBMI and DIC techniques applied for the dynamic testing of a cable stay-bridge. Considering their operational limitations and performance capabilities, a number of alternative observation scenarios were performed to monitor the behavior of the main elements of the structure (i.e., the deck, the pylons and cables).

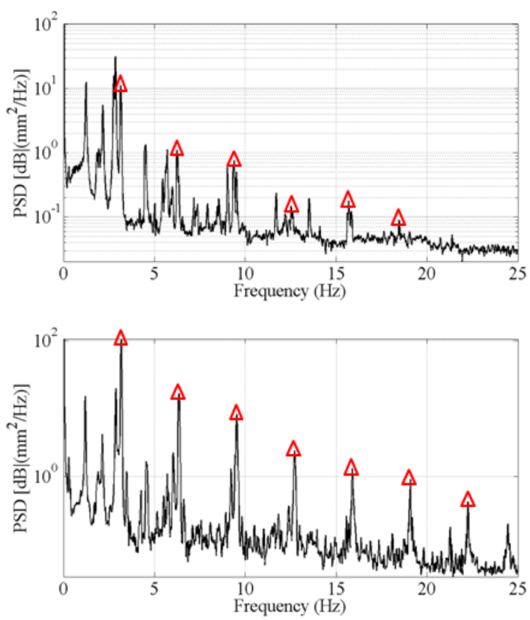

Figure. 9 PSDs of the GBMI data acquired from the long cable under ambient load (up) and during the static load test (down).

Particularly, this study concentrates on the deck and cable dynamic properties, whereas emphasis is placed on the study of deck-cable dynamic interaction.

Analysis reveals the dominant frequencies and mode shapes of the structure. Also, an experimental computation of cable tension forces was proved feasible using the GBMI measurements. Finally, the parallel use of the GBMI and DIC systems revealed their high potential for use as independent monitoring systems as well as the benefits arising from their combined use.

Acknowledgements
Acknowledgements are due to Dr. P.S. Karydakis, structural engineer and F. Papadimitriou and A. Panagakis Traffic & Maintenance Manager and Head of Road Maintenance of Attikes Diadromes S.A., for their cooperation during field measurements and the fruitful discussions on the results interpretation. Also, sincere thanks are due to the entire group of surveying engineers from the NTUA that assisted in surveying field work and office computations.

References

Brincker, R., Zhang, L. and Andersen, P. (2000). Output-only Modal Analysis by Frequency Domain Decomposition, In: *Proc. of ISMA25*, Vol.2, pp.717-723.

Brincker, R., Kirkegaard, P.H. (2010). Special issue on Operational Modal Analysis, In: *Mechanical Systems and Signal Processing 24*, pp.1209-1212.

Brownjohn, J.M.W, Magalhaes, F., Caetano, E. and Cunha, A. (2010). Ambient Vibration Re-testing and Operational Modal Analysis of the Humber Bridge. Engineering Structures, Vol. 32.

Caetano, E., Silva, S. and Bateira, J. (2011). A Vision System for Vibration Monitoring of Civil Engineering Structures, Experimental Techniques, July / August.

Choi, H-S., Cheung, J-H., Kim, S-H. and Ahn, J-H (2011). Structural Dynamic Displacement Vision System Using Digital Image Processing, NDT & E International, Vol. 44, No. 7.

Gikas, V. (2012). Ambient Vibration Monitoring of Slender Structures by Microwave Interferometer Remote Sensing, Journal of Applied Geodesy, Vol. 6, No. 3-4.

Gikas, V., Karydakis, P., Mpimis, A., Piniotis, G. and Perakis H. (2014). Structural Integrity Verification of a Cable-stayed Footbridge Based on FEM Analyses and Geodetic Surveying Techniques, Accepted by: *Survey Review*.

Gikas, V., Karydakis, P., Mpimis, T., Piniotis, G. and Perakis, H. (2014). Nodestructive Load Testing of a Single-Span, Cable-Stayed Bridge: Testing, Instrumentation and Preliminary Results, In: *Proc. of FIG Congress*, Kuala Lampur, Malaysia, June 16–21.

Gikas, V., Karydakis P., Piniotis G., Mpimis T., Papadimitriou F, Panagakis A. (2014). Design and Implementation of a Multi-Sensor Monitoring System for Structural Integrity Assessment: The Case of Attiki Odos, Pallini Cable-Stayed Bridge, In: *Proc. of IBSBI*, Athens, Oct. 16–18.

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

Hoa, L.T., Tamura, Y., Yoshida, A. and Anh, N.D. (2010) Frequency Domain versus Time Domain Modal Identifications for Ambient Excited Structures, In: *International Conference on Engineering Mechanics and Automation (ICEMA 2010),* Hanoi, July 1-2.

Kaloop, M.R., Hu, J.W., Sayed, M. and Seong, J. (2015). Structural Performance Assessment Based on Statistical and Wavelet Analysis of Acceleration Measurements of a Building during an Earthquake, Shock and Vibration, Article ID 631205.

Kaloop, M. R., Hu, J. W. (2015), Optimizing the De-noise Neural Network Model for GPS Time-series Monitoring of Structures, Sensors, Vol. 15, No 9, pp. 24428-24444.

Koh, H-M., Park, W. and Choo, J.F. (2009). Achievements and Challenges in Bridge Health Monitoring Systems and Intelligent Infrastructure in Korea, In: *4th Int. Conf. on structural health monitoring of intelligent infrastructure*.

Kuras, P., Ortyl, L. (2014). Selected Geometric Aspects of Planning and Analysis of Measurement Results of Tall Building Structures Using Interferometric Radar, In: *Geomatics and Environmental Engineering 2014,* Vol.8, No 3, pp.77-93.

Morlier, J., Salom, P. and Bos, F., (2007). New Image Processing Tools for Structural Dynamic Monitoring, Key Engineering Materials, Vol. 347.

Moschas, F, and Stiros, S. (2015) Dynamic Deflections of a Stiff Footbridge Using 100-Hz GNSS and Accelerometer Data, Journal of Surveying Engineering, DOI: 10.1061/(ASCE)SU.1943-5428.0000146.

Pieraccini, M. 2013. Monitoring of Civil Infrastructures by Interferometric Radar: A Review, The Scientific World Journal, Vol. 2013.

Yi, T-H., Lei, Y., Chen, H-P., Ye, X-W., Kang, F. and Wang, H. (2014). Technology Developments in Structural Health Monitoring and Integrity Maintenance, The Scientific World Journal.

Waterfall P-W., Macdonald J-H-G., McCormick N-J. (2012) Targetless Precision Monitoring of Road and Rail Bridges using Video Cameras *6th Int. Conference on Bridge Maintenance, Safety and Management*.