Multi-sensor measurement of dynamic deflections and structural health monitoring of flexible and stiff bridges

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ABSTRACT: We investigated the response of bridges of different types to controlled and to wind and traffic-induced excitations; the emphasis was on deflections, derived from recordings of geodetic sensors and accelerometers (output-only analysis). Our focus was to push the limits of the existing experimental techniques, in order to cover not only flexible, but also stiff structures, and to present independently validated results. Our study focused on a 700m long, thin-deck cable-stayed bridge, a stiff steel pedestrian bridge, a historic composite (masonry/steel) train bridge and a 30m long, gradually decaying, currently swaying pedestrian timber bridge.

Our basic strategy was first to develop data measurement and processing techniques using controlled (supervised learning) experiments, and then,

(1) use collocated, redundant and distributed geodetic sensors (GPS/GNSS and Robotic Total Stations, RTS), as well as accelerometers, in order to record bridge excitations, especially controlled excitations leading to free attenuating oscillations;

(2) develop techniques to denoise recordings of various sensors based on structural/logical constraints and sensor fusion, compensating for the weaknesses inherent in each type of sensor), validate results and avoid pitfalls;

(3) monitor the episodic and gradual decay of a pedestrian bridge, through repeated surveys under similar loading and environmental conditions and using similar instrumentation.

The output of our studies is to confirm the potential of modern sensors to measure, under certain conditions, reliable mm-level dynamic deflections even of stiff structures (3-6Hz dominant frequencies) and to provide firm constraints for structural analysis, including evidence for changes of first modal frequencies produced by structural decay, even to identify dynamic effects such as foundations response to dynamic loading.

1 INTRODUCTION

In the last 20 years GPS (GNSS, Global Navigation Satellite Systems in general) have been used for the monitoring of deflections of cable-stayed bridges, a topic of major interest especially because of the impressive lateral deflections of the Millennium Bridge in London during its opening (Dallard et al, 2001). Apart from GPS, other geodetic sensors such as robotic theodolites (Robotic Total Stations, RTS, known also as Total Positioning Systems, TPS) and image-processing techniques have been used to measure stiffer bridges. Currently, probably more than 100 bridges in all parts of the world have been monitored using geodetic techniques, some in specific conditions (for example during the NY Marathon; Kogan et al, 2008), some in the framework of permanent monitoring systems.

However, there are two problems with bridge geodetic monitoring.

The *first* is the problem of metrology, corresponding to questions of the type: what is the range of displacements of a bridge that can be measured by geodetic sensors, whether an apparently "good" measurement of dynamic displacement is reliable, and under which conditions and with which techniques it is possible to measure dynamic deflections of a stiff or a flexible bridge using instantaneous GPS positioning which is contaminated by long-period noise (see Figure 1).

The *second* is the problem of structural significance of measurement-derived displacements. A common question arising is whether and under which conditions analysis of deflection measurements can lead to estimates of natural frequencies of a structure.

In this article we review unpublished and previously presented results and ideas from monitoring deflections of several bridges of different types in Greece, both long-period and stiff structures (roughly, modal frequencies below or above 1Hz), using a specific methodology which was developed, and summarize some conclusions of broader importance for the response of bridges to various excitations and for their structural health.

Figure 1 GPS (GNSS) recordings are contaminated by long and short-period noise, as shown in (a), in which a white curve indicates the long-period signal. If this last signal is subtracted, a short-period signal is computed as in (b), and using filtering, dynamic deflections are computed (c). If this repeated filtering is reliable, remnant noise is of the order of a few mm and the graph of dynamic displacements will be consistent with accelerograph recordings (d). In (d) a free attenuation oscillation that can provide information on a first natural frequency is marked by a red frame. Modified after Moschas & Stiros (2011).

2 MONITORING METHODOLOGY

Our methodology was developed in the last 15 years and has <u>three main characteristics</u>

(i) Development of measurement and data processing methodology in representative, controlled experiments in which the measurement conditions and the expected output was known. Under these conditions, the response (accuracy etc.) of the instruments used (mostly GNSS and Robotic Total Stations with upgraded software and high-quality reflectors, in combination with accelerometers) can be assessed, and there can be developed reliable techniques for denoising data (supervising learning approach). This methodology included a computer code for spectral analysis of RTS data characterized by unstable sampling rate (Psimoulis & Stiros, 2012), specifying also statistical uncertainty limits of spectral peaks (Pytharouli & Stiros, 2008).

(ii) Use of collocated and redundant sensors of different types to record dynamic and semistatic defections during bridge excitations. This permits to double-check the output of each instrument and avoid specific types of noise, especially blunders (for example, dynamic multipath in GPS (Figure 2; cf. see section // below), which may be interpreted as high amplitude deflection) and to compensate for the weaknesses inherent in each type of sensor (for example in oscillations above 1Hz GPS overestimates peak amplitude while RTS underestimates them).

(iii) Measurements satisfying certain conditions, in particular focusing on forced and free attenuating oscillations (see Figure 1d, inset) permitting to directly derive modal characteristics of bridges, and exploitation of structural and logical constraints in the analysis of monitoring data; for example, comparison of measurements during consecutive intervals of no motion/excitation and of controlled excitation, in order to evaluate noise and statistical significance of recorded deflections.

Figure 2. Results of an experiment to simulate dynamic multipath, i.e. noise produced by reflections of a passing two-wagon train, recorded by a GPS receiver setup 2m away from the train track on stable ground. Apparent dynamic displacements may be misinterpreted as dynamic deflections of a bridge. Right and left column indicate solutions with two different software packages and show the signature of the two wagons. After Moschas and Stiros 2014 GPSSol. Multipath amplitude is variable, and may range between a few mm to a few meters (Moschas et al, 2013 SSS)

2.1 *Controlled experiments to derive measurement methodology (Dynaic multipath??)*

A wide range of controlled experiments were used to constrain the measuring strategy. These included measurements of known characteristics, for example recordings of dynamic deflections using sensors fixed on a shaking table (Psimoulis et al., 2008), or simulation of GPS measurements next to a passing train (Moschas and Stiros, 2014). In this last case secondary reflections of the satellite signal to the highly reflective surfaces of the train gave the impression of an unrealistically high deflection (Figure 2; see also section 3.2). This is a basic explanation for some cases of abnormally high deflections of stiff bridges that are reported by various authors.
An output of this study is to confirm the potential of application of GPS and of RTS in monitoring not only long, high-period bridges, but of stiffer bridges as well, expanding the limits of application of GPS and RTS (Moschas & Stiros, 2011; Stiros & Psimoulis, 2012; Moschas et al., 2013///).
Concerning RTS, their main problem is the low measurement rate of commercial instruments. To overcome this problem, we used an upgraded built-in software permitting to collect measurements with a mean rate of 7Hz and a resolution of 0.01sec. This, in combination with high quality reflectors (AGA-type reflectors) offers an accuracy of ±1-2mm for isolated measurements (not mean values) and makes RTS suitable for monitoring of 3-D deflections of relatively stiff structures (Psimoulis & Stiros, 2008).

2.2 *Use of collocated instruments*

Because we are fully aware of the limitations of all sensors (various types of noise/errors, malfunctions, etc.) our field studies was based on collocated sensors, mostly more than one RTS, GPS and accelerometer were set next or on top of the other, in order to limit the effects of sensor malfunction and to compensate for the weaknesses inherent in each type of sensor (Figure 3a). For example, GPS has higher sampling rate (usually 10 to 100Hz for structural monitoring, compared to 1Hz used for conventional geodetic work), but is noisy, while RTS has a smaller sampling rate but lower noise, so their fusion leads to reliable and useful results (Psimoulis & Stiros, 2008).

2.3 *Structural constraints and free attenuating oscillations*

An efficient way to control sensor noise is to compare recordings during intervals of excitation with measurements of no excitation (cf. section 3.3). Furthermore, if it is possible to record the response of a bridge during free attenuating oscillations, confirmed by accelerograph data, and compute its first modal frequency.

3 CASE STUDIES
We present results from the monitoring of four bridges in Greece, with quite different structural characteristics. In the monitoring of these cases we adopted/developed the methodology proposed (instrumentation and data processing method).

3.1 *The Evripos (Chalkis) cable-stayed bridge*

The Evripos (Chalkis) cable-stayed bridge is about 700m long with a very thin (45cm) deck, the first cable-stayed bridge constructed in Greece. The dynamic response of this bridge, especially during an earthquake, derived from the analysis of accelerometers and geodetic sensors have been discussed in the past by Lekidis et al (2005). Monitoring results discussed derive from a survey based on several fully or nearly collocated instruments at the midspan of the bridge:

force-balance accelerometers, two passive reflectors each sighted by a different RTS, and four GPS receivers, two of which with large chock ring antennas to minimize secondary reflections (multipath). These sensors (Figure 3a), in combinations with sensors on stable ground were focusing on the response of the bridge to traffic, during a wind-free day, and in particular on traffic characterized by intervals of quiescence interrupted by excitations produced by lorries and busses, so that the response of the bridge to discrete loading events can be described.

   Figure 3b summarizes some aspects of the response of the deck of the bridge to a passing lorry, vertical deflections derived from GPS and RTS recordings. Noise and signs of dynamic excitation characterizes both deflections records, but the signature of the lorry is clear, a maximum deflection of 20-30mm, indicating a flexible bridge deck.

Figure 3. a: Monitoring instruments at the midspan of the Evripos Bridge. Two circular RTS receivers, two force-balance accelerometers and four GPS receivers (two of which with large chock-ring antennas) are visible. b: Vertical deflections produced by a passing track recorded by one of the RTS and one GPS.

3.2 *The Gorgopotamos Historical train bridge*

This is a historical bridge train in central Greece, next to the town of Lamia. The bridge consists of masonry pillars, up to 32m high, and a steel truss deck; each opening is about 28-30m long (Figure 4). This bridge has suffered much damage during the World War II and this has some impact on its dynamic behavior. In addition, it is founded on marls the mechanical behavior of which is different in dry and wet periods. When excited by trains, this bridge produced strong vibrations which forced to low train velocities, and is currently out of use, because the whole line has been abandoned.

Measurements reported were based on RTS and GPS, focusing on the response of the midspan of a central opening during the passage of trains of different types (light service trains, passenger trains and long, heavy freight trains) under different environmental conditions (dry marls at the foundations, responding as solid rock and wet marls responding as a compressible material). Figure 4a shows the response of the bridge in the vertical axis when excited by a heavy freight train during a wet season. Measurements analyzed were based on RTS; measurements by GPS (with common, geodetic antennas) were highly contaminated by dynamic multipath, leading to apparent vertical deflections exceeding one meter in amplitude (Moschas et al, 2013). This justifies the use of collocated sensors of different types.

The bridge response to a freight train was characterized by semi-static and dynamic deflections of several mm (Figure 4). It is of prime interest the peak in deck subsidence when the train was first entering the 32m-long opening, leading to an additional pulse-type deflection of several mm. This effect was observed only in heavy loads (freight trains) and only when marls in foundations were wet. It reflects the first impact and a soil-structure interaction effect.

Figure 4. (Left): A train passing through the historical Gorgopotamos Bridge produces dislocations recorded by a Leica RTS (shown in foreground) sighting to an AGA super reflector at the midspan of the bridge (shown in the inset). The GPS signal recorded by an antenna collocated with the reflector was highly contaminated by dynamic multipath. (Right) Observed vertical displacement and its semi-static and dynamic components. In the latter, an arrow indicates a pulse, reflecting the first impact, a soil-structure-loading interaction effect.

3.3 *A steel footbridge in Athens*

A stiff footbridge crossing the Kifissos Avenue in Athens was tested during controlled excitations by a group of well-trained people to produce freely attenuating oscillations. The footbridge consists of a steel truss deck supported by four reinforced concrete pylons through isolators. The total length of the deck is 62m and is divided into a central span 41.5m long and two side-spans, each 10.25m long (Figure 5). Tube-section members with an external diameter of 244mm were used for the construction of the truss which has a square cross-section. The bridge was designed to comply with the Eurocode EC-3 specifications, implying a first natural frequency of the central span >3Hz and maximum vertical deflections at the midspan <30mm. A preliminary FEM analysis revealed a dominant vertical frequency of 4.32Hz and maximum vertical oscillations of 4-5mm at the midspan (Moschas and Stiros 2013, SCHM).

The vibration control system consisted of two compact 10Hz GNSS receivers installed on the top of the truss (hence with undisturbed view of satellites) collocated with and two AGA supertype reflectors, each sighted by one RTS on the ground, as well as event-triggered force-balance accelerometer. Discrete, controlled excitations were produced by a group of people with a mass of 450kg, jumping or running, with their movement suddenly freezing to produce free attenuating oscillations. This produced excitation events with peak vertical accelerations between 0.10-2.00g, occasionally giving the sense of an imminent collapse, and which were recorded by all sensors along with data from preceding and following intervals of no movement. Analysis of data following the process shown in Figure 1 indicates consistency of GPS and RTS data within an error margin of 1-2mm. Figure 6 summarizes lateral and vertical dynamic deflections along with accelerometer recordings for a certain event.

Events satisfying certain criteria (mainly the criterion of a free attenuating oscillation derived from accelerometer measurements) were further processed based on a weak sensor fusion approach. Results are reported in ENGSTR, SCHM, and in this article we focus on the contrast of spectra of deflections of the sensors (GPS, RTS) during intervals of motion and of no motion, as well as on components along the main axis (longitudinal), the lateral and the vertical ax-

is. Spectra were computed with a least-squares based code to provide estimates of statistical significance and to cover RTS measurements which are not characterized by a constant sampling rate (Pytharouli & Stiros 2008; Stiros & Psimoulis 2013 ENG STR Gorgo). Figure 7 shows that significant spectral peaks are observed only during the excitations and only along the vertical and lateral axis, as is expected in a stiff bridge of this type.

Figure 5. The steel footbridge in Athens. Monitoring sensors were fixed on the top of the truss, at the middle of the main, central span, so that GPS is not affected by multipath.

Figure 6. An example of dynamic displacements derived from GNSS and RTS, in comparison with accelerometer measurements. Mark consistency of results, but also noise of a few mm in deflections (modified from Fig 9 Kifissos SCHM,

Figure 7. A composite graph explaining how spectra of GPS and RTS-derived deflections of the steel pedestrian bridge of Figure 5 can be used as logical and structural constraints to assess the quality of computed deflections. Left and right column correspond to intervals before excitation, the central column to a free attenuation interval (see Figure 1d). Statistically significant spectral peaks are observed only during the excitation interval, and only along the vertical and lateral axis. In all other cases, noise only is observed. In all graphs superimposed spectra of the two sensors are shown. After Moschas and Stiros 2013 SCHM).
Ayto to sxhma thelei na emfanistoyn ta RTS/GPS to ena mayro to allo kokkino

3.4 *The Kanellopoulos timber footbridge in Patras*

The Kanellopoulos timber footbridge was constructed in 2000 using GLULAM wood and certain steel elements. The deck has a total length of about 30m and width of 2.9 m and is formed by two main twin horizontal parallel beams, stiffly connected at their edges by twin transversal beams. It is also supported by two vertical arches leaving a midspan of 26.5 m (Figure 8; for details see // /). Constructional problems (stiffeners beneath the deck omitted during the construction and damage by an extraordinary for the area slash icing event; Thalla and Stiros, 2018), transformed this initially stiff bridge to a laterally swaying bridge (see video Supplement in ///). The decay of this structure has been recorded by several annual monitoring surveys between 2007 and 201??, under identical measuring, loading and environmental conditions, and is summarized in Figure 8b. This figure shows an impressive episodic and then gradual shift of the first lateral natural frequency of the bridge. This result is fully reliable because it comes from several instruments and free-attenuating oscillations which are dominated by a main modal frequency of the bridge. Decay was mainly affecting lateral stiffness, and vertical stiffness was

little affected, so that its vertical first natural frequency did not drop below 6Hz.
This result was derived both by accelerometer and GPS data using 100Hz GNSS measurements (Moschas //); RTS data cannot record oscillations of this frequency. Clearly, the use of GPS was possible because this bridge has no large reflective surfaces to produce important multipath.

Figure 8. Left, the Kanellopoulos timber bridge in Patras, Greece, Right: estimates of first lateral frequency derived from RTS and confirmed by GPS. Each dot represents a different estimate. A gray line indicates approximately a damage interval. Modified after ???

4 DISCUSSION AND CONCLUSIONS

Experimental evidence (refs) and evidence from several bridges summarized above indicates that geodetic instrumentation is not limited to long cable- stayed bridges which are characterized by deflections with an amplitude of the order of tens of centimeters when excited by heavy trucks (Brownjohn et al, 2014), but it can cover also short, stiff bridges (openings <30m) with modal frequencies of the order of 3Hz and deflections of a few mm.

Geodetic monitoring, however, has various limitations, and is not free of problems and misconceptions. For example, errors such as dynamic multipath (Figure 2) may hamper results, and give the wrong impression of excessive dynamic dislocation which are not possible from the structural point of view and from the everyday experience. Collocated sensors especially of different types can solve this ambiguity. This is one of the major points of our monitoring approach.

Another problem is the significance and further use of displacement data. For example, in Figure 1 an excitation is recorded by GPS and RTS between seconds 20 and 70, but their spectra cannot readily provide any information for the dynamic characteristics of the bridge (natural frequencies etc.) and will be dominated either by noise or by the characteristics of the excitation (velocity of a passing vehicle, frequency of passing vehicles, etc.). On the contrary, the spectrum of the free attenuating oscillation marked in Figure 1d describes a first natural frequency.
The overall conclusion is that recent evidence indicates that the limits of applications of geodetic sensors in bridge monitoring have been broadened, and this opens new horizons in structural health monitoring.

5 REFERENCES

Brownjohn, J.; Koo, K.Y.; Scullion, A.; List, D. Operational deformations in long-span bridges. Struct. Infrastruct. Eng. **2014**, 11, 556–574

Dallard, P.; Fitzpatrick, A.J.; Flint, A.; Le Bourva, S.; Low, A.; Ridsdill, S.; Willford, M.R. The London Millennium Footbridge. Struct. Eng. **2001**, 79, 17–33

Kogan, M.G., W. Kim, Y. Bock, A. Smyth. Load Response on a Large Suspension Bridge during the NYC Marathon Revealed by GPS and Accelerometers. Seismological Research Letters, Vol. 79, Number 1, January/February 2008 doi:10.1785/gssrl.79.1.12

Lekidis, V., Tsakiri, M., Makra, K., Karakostas, C., Klimis, N. and Sous, I. (2005), "Evaluation of dynamic response and local soil effects of the Evripos cable-stayed bridge using multi-sensor monitoring systems", Engineering *Geology*, **79**(1-2), 43-59.

Meng X, Dodson AH, Roberts GW. Detecting bridge dynamics with GPS and triaxial accelerometers. Engineering Structures. 2007; 29(11):3178–84.

Moschas, F, Stiros, S. Measurement of the dynamic displacements and of the modal frequencies of a short-span pedestrian bridge using GPS and an accelerometer. *Engineering Structures*, 33, 10-17, 2011

Moschas, F., Psimoulis, P. and Stiros, S., GPS-RTS data fusion to overcome signal deficiencies in certain bridge dynamic monitoring projects, *Smart Structures and Systems*, 12, 251-269, 2013, doi: 10.12989/sss.2013.12.3_4.251

Moschas, F, Stiros, S. Dynamic deflections of a stiff footbridge using 100Hz GNSS and accelerometer data. *J. Surv Eng. (ASCE),* 141(4), 2015, http://dx.doi.org/10.1061/(ASCE)SU.1943-5428.0000146

Moschas, F, Stiros, S. Measurement of the dynamic displacements and of the modal frequencies of a short-span pedestrian bridge using GPS and an accelerometer. *Engineering Structures*, 33, 10-17, 2011.

Moschas, F. and Stiros, S. Dynamic multipath in structural bridge monitoring: an experimental approach. *GPS Solutions,* 18(2), 209-218, 2014.

Moschas, F. and Stiros, S. Three dimensional dynamic deflections and natural frequencies of a stiff footbridge, based on measurements of collocated sensors, *Structural Control and Health Monitoring*, 21 (1) , 23-42, 2014

Moschas, F., Psimoulis, P. and Stiros, S., GPS-RTS data fusion to overcome signal deficiencies in certain bridge dynamic monitoring projects, *Smart Structures and Systems*, 12, 251-269, 2013

Nakamura S. GPS measurement of wind-induced suspension bridge girder displacements. J Struct Eng ASCE 2000;126(12):1413- 9.

Psimoulis, P. and Stiros, S. Measuring deflections of a short-span railway bridge using a Robotic Total Station (RTS), *Journal of Bridge Engineering (ASCE),* 18(2), 182-185 (2013); http://dx.doi.org/10.1061/(ASCE)BE.1943-5592.0000334

Psimoulis, P., Stiros, S., Measurement of deflections and of oscillation frequencies of engineering structures using Robotic Theodolites (RTS), *Engineering Structures*, 29 (12), 3312-3324, 2007.

Psimoulis, P. and Stiros, S. A supervised learning computer-based algorithm to derive the amplitude of oscillations of structures using noisy GPS and Robotic Theodolite (RTS) records, *Computers and Structures*, 92-93, 337-348, 2012.

Psimoulis, P., Pytharouli, S., Karambalis, D., Stiros, S. Potential of Global Positioning System (GPS) to measure frequencies of oscillation of engineering structures, *Journal of Sound and Vibration* 318(3), 606-623, 2008.

Pytharouli S., Stiros, S, Spectral analysis of unevenly-spaced or discontinuous data using the "Normperiod" code. *Computers and Structures*, 86, 190-196, 2008.

Roberts, G. W., X. Meng, and A. H. Dodson (2004). Integrating a global positioning system and accelerometers to monitor the deflection of bridges. Journal of Surveying Engineering ASCE 130 (2), 65-72

Stiros, S, Moschas, F., Rapid decay of a timber footbridge and changes in its modal frequencies derived from multi-annual lateral deflection measurements, *J Bridge Engineering (ASCE),* 19(12), 05014005, 2014

Stiros, S. and Psimoulis, P. Response of a historical short-span railway bridge to passing trains: 3-D deflections and dominant frequencies derived from Robotic Total Station (RTS) measurements. *Engineering Structures*, 45, 362-371, 2012

Tamura, Y., Matsui, M., Pagnini, L., Ishibashi, R., Yoshida, A., Measurement of wind-induced response of buildings using RTK GPS, Journal of Wind Engineering and Industrial Aerodynamics 92 (2002) 1783–1793.