Measuring the Displacements of a Rigid Footbridge Using Geodetic Instruments and an Accelerometer

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ABSTRACT:

Systematic experimental studies have shown the potential of geodetic instruments (GPS, Robotic Theodolites-RTS) with high sampling rate (up to 10Hz) to measure dynamic displacements of relatively rigid structures (oscillation frequency > 1Hz). Based on these results, we used a dense measuring network including GPS instruments, robotic theodolites and an accelerometer to measure the dynamic response of a 40m-long, stiff steel footbridge in Athens, Greece, excited by synchronized vertical jumps of pedestrians. Spectral analysis of the accelerometer, GPS and RTS recordings defined the bridge oscillation frequency on the vertical axis to be 4.3-4.4Hz. Furthermore analysis of the GPS and RTS measurements indicated a mean vertical dynamic displacement of 3.9 mm for the GPS instrument and 3.5 for the RTS. The results of this study indicate that geodetic instruments are able to directly measure the displacements of a wide variety of engineering structures, making them a very useful tool for structural health monitoring.

1. INTRODUCTION

Monitoring the deformations of structures due to dynamic loads like wind, traffic or earthquakes has been for centuries a dream for engineers. Until recently accelerometers have been the most common instrument for measuring the dynamic response of structures in terms of acceleration. Double integration of measured accelerations, however, leads to very noisy and inaccurate estimates of displacement (Stiros, 2008) while extensometers etc. can measure only relative displacements between adjacent structural elements.

In the last decade, a huge step in the measurement of deflections of major structures has been done with the advent of GPS and Robotic Total Stations (RTS), which permit to measure instantaneous coordinates relative to a fixed coordinate system.

Until now, GPS and RTS have successfully been used in the measurement of displacements of major flexible structures like cable stayed and suspension bridges (Roberts et al., 1999; 2004; Lekidis et al., 2005; Chan et al., 2006), towers (Lovse et al., 2005; Brewer et al.,2008) or high-rise buildings (Celebi, 2000; Tamura et al., 2002; Chan et al., 2006; Kijewski Correa et al., 2006; Li et al., 2006). Such structures are characterized by relatively low natural frequencies (less than 1 Hz) and large displacements (>0.1m).

The next big challenge is to use high rate GNSS (up to 100Hz) and RTS (up to 10Hz) to measure displacements of relatively stiff structures characterized by high oscillation frequencies (>2Hz) and deflections of only a few millimetres.

In the present paper we present a case study of measurement of the oscillations of a stiff footbridge using noisy GPS and RTS recordings, in combination with signal analysis techniques and accelerometer data.

2. PREVIOUS WORK

A number of studies have highlighted the limitations of geodetic instruments in structural monitoring. GPS measurements are contaminated by low-frequency (<1Hz)/ high amplitude (some centimetres) ambient noise which covers mm-scale oscillations (Kijewsi Correa et al., 2006), and in addition is affected by multipath (Brunner, 2006). Robotic theodolites suffer from an instability in the sampling rate (jitter effect) and loss of oscillation cycles in the cases of high-frequency oscillations (clipping effect) (Psimoulis and Stiros, 2007).

Still, Meng et al. (2007) were able to identify the oscillation amplitude (10-80mm) and frequency (1.73Hz) of the Wilford suspension footbridge in Nottingham using combined GPS and accelerometer measurements after a suitable filtering.

Psimoulis and Stiros (2007) and Psimoulis et al. (2008) have identified oscillation amplitudes of some millimetres and frequencies up to 4 Hz from RTS and GPS measurements using special signal analysis techniques, while oscillations of high frequencies and low amplitudes have been identified by Casciati and Fuggini (2010) using GSP.

These indicate that it is possible to use geodetic instruments for the monitoring of stiff engineering structures.

3. FOOTBRIDGE CHARACTERISTICS

The bridge analyzed in the present study is a steel pedestrian footbridge crossing the Kifissos Avenue in Athens, Greece. The bridge deck consists of three spans, a central one 41.5 m long and two sidespans, each 10.25 m long. Each span is formed by a truss of rectangular section based on four reinforced concrete pylons (Figs. 1,2) and corresponds to a simply supported beam.

The bridge was built to satisfy the specifications of Euro-Code 3 in particular displacements <3 cm and dominant modal frequency > 3 Hz.

During our experiments, the middle span of the bridge was excited by synchronized vertical jumps of a group of pedestrians (approximate period of the excitation 1sec). The displacements of the bridge during the excitation were significant and felt by the pedestrians jumping on the bridge deck.

4. BRIDGE INSTRUMENTATION AND DATA COLLECTION

In this study we focus on a (rover) GPS receiver and an AGA reflector which had been fixed on the top of the truss at the midspan of the bridge, so that both instruments could precisely follow the bridge movement.

A rover compact-type Topcon Hipper Pro receiver recording at a rate of 10 Hz was used, while the reflector was observed by a Leica TCA 1201 Robotic Total Station set on the ground, approximately 60m away from the reflector and recording at a 10Hz nominal sampling rate. A reference (base) GPS receiver was also installed at a 60m distance from the bridge and was recording also at a 10Hz rate. The measuring conditions were favorable for the GPS receivers, which were free of any obstructions of the view of the horizon and exposed to minimal secondary reflections.

In addition to the geodetic sensors, the bridge movement was recorded by an event-triggered AC-23 GeoSIG-type accelerometer with dedicated GPS timing, recording at a rate of 250 Hz, and with its axes aligned with the longitudinal, lateral and vertical axes of the bridge. The monitoring instrumentation is presented in Figure 2.

The bridge was excited several times by a group of 6 people with a total weight of 450kg by synchronized jumps. In the present study we focus on one of the excitations that caused significant bridge displacements.

Figure 1. View of the pedestrian footbridge crossing the Kifisos Avenue in Athens (up) and location of the sensors used to measure the bridge oscillations (down).

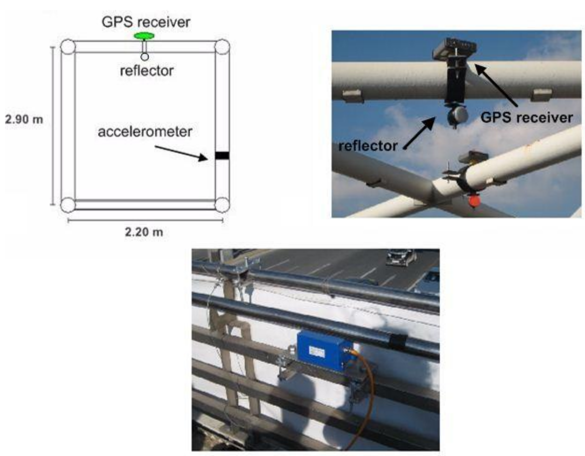

Figure 2. A vertical cross section of the truss bridge showing the location of the monitoring instruments- details in the two photos.

5. METHODOLOGY AND DATA ANALYSIS

The methodology followed to identify the bridge oscillation amplitude and frequency consisted of the following steps:

a) Preliminary processing and coordinate transformation:
GPS measurements from the base and rover receivers were processed using the Topcon Pinnacle software to produce instantaneous Cartesian coordinates of the rover receiver in the WGS'84 coordinate system. RTS measurements were available in Cartesian coordinates relative to the position of the RTS instrument.

In the present paper we focus on the GPS/RTS vertical coordinates, which were then transformed into a time series of apparent vertical displacements around an origin representing the equilibrium level of the monitoring point.

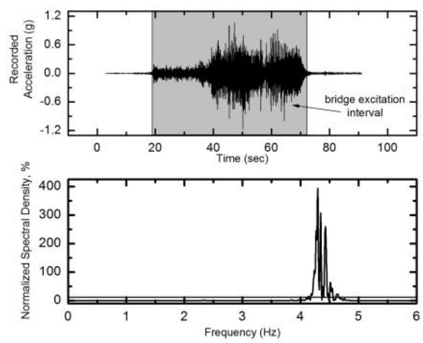

Figure 3. Up: Recorded acceleration used to constrain the excitation interval in geodetic time series. The recorded maximum acceleration was 1.1g. Down: Spectrum of recorded accelerations. Significant peaks are between 4.3 and 4.4Hz.

b) Filtering of the apparent displacements from GPS and RTS
The time-series of apparent displacements of GPS and RTS are contaminated by noise (Fig. 4), and the most effective way to analyse them is to decompose them into long and short period components. This decomposition was based on a simple but efficient filter, derived from supervised learning experiments (a moving average filter with step 0.1 second and 45 seconds window; Moschas and Stiros 2011). A characteristic result is shown in Figure 4. The long-period component contains long-period noise plus semi-static displacements, while the short-period component contains dynamic displacements plus remnant noise (Moschas and Stiros, 2011).

c) Identification of oscillation interval from accelerometer measurements
As can be deduced from Fig. 4, both the apparent displacements and their components contain noise, and for this reason it was not easy to identify the oscillation interval. The latter was identified using the accelerometer recordings (Figure 3). This interval is marked in Fig. 4.

d) Identification of oscillation frequency and amplitude
The spectra of the short-period components of displacements corresponding to the intervals before, during and after the bridge excitation (Fig. 4) were computed in order to investigate the existence of an oscillation signal and eventually detect oscillation frequencies. The spectral analysis, summarized in Fig. 5, was based on the Lomb Periodogram and the "Normperiod" code, permitting to analyse non-equidistant RTS measurements and to estimate the level of significance of the computed spectral peaks (Pytharouli and Stiros 2008).

e) Data evaluation

The results of Fig. 5 in comparison with those of Fig. 3 permit to recognize that both GPS and RTS recorded a signal of dynamic displacement from which the spectral characteristics of the oscillations were precisely computed. In particular, the peak of 4.3-4.4Hz deduced from accelerometer data (Fig. 3) can be identified in the spectra of the excitation interval for both the GPS and RTS data (4.43Hz), but not in the intervals before and after it (Fig. 5). Still, it is not easy to calculate the amplitude of dynamic displacements, especially from GPS data. For this reason we adopted the algorithm, proposed by Psimoulis and Stiros (2011), developed from supervised learning techniques, and estimated the values of mean dynamic displacements shown in Table 1, approximately 4mm.

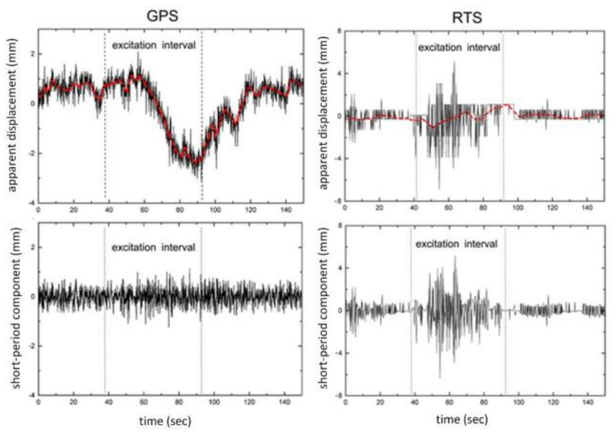

Figure 4. Upper row: Time series of GPS and RTS apparent displacements. The red line corresponds to the long-period component. The low-frequency/high-amplitude signal in the GPS time-series represents either semi-static displacement or long-period-noise. (Lower row) Short-period components resulting after subtracting the long-period time–series from the apparent displacements. The result is the dynamic displacement plus remnant noise.

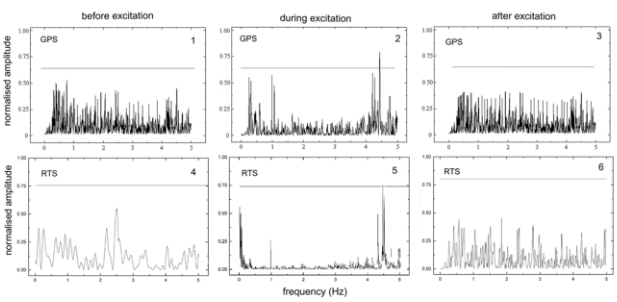

Figure 5. (1-3) Spectrograms of the short-period components of apparent displacements deduced from GPS (upper row) and RTS (lower row) for the intervals before, during and after the bridge excitation (left, center and right column, respectively). Red lines mark the 95% statistical significance level of peaks.

Table 1. Bridge oscillation amplitude and frequency as estimated by GPS, RTS, accelerometer and FEM modelling.

	GPS	**RTS**	**Accel**	**FEM**
mean vertical deflection (mm)	3.8±1.3	3.4±0.5		~3.5
dominant frequency (Hz)	4.43	4.43	4.43	4.3-4.4

6. CONCLUSION

In the present study we summarized a methodology for deducing oscillation parameters (amplitude, frequency) of a stiff bridge from noisy GPS and RTS measurements using constraints from accelerometer recordings and signal analysis techniques. Vertical dynamic displacements of approximately 3.8 and 3.5 mm were computed from filtered GPS and RTS measurements, respectively, while a 4.43Hz oscillation frequency was identified, corresponding to the first natural frequency of the footbridge. These values were consistent with estimations from accelerometer measurements and a FEM model (Psimoulis and Stiros (2011).

The result of the present study reveals the high potential of modern geodetic instruments for recording dynamic movements of relatively stiff structures, exceeding the limits assumed so far (natural frequencies below 1Hz) and making them a very useful tool for structural health monitoring.

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