GNSS FOR STRUCTURAL DEFORMATION AND DEFLECTION MONITORING: IMPLEMENTATION AND DATA ANALYSIS

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Abstract: GNSS, particularly GPS has been used for monitoring structural deformation and deflection for more than a decade. While it is used for this purpose, GPS has demonstrated its feasibility and obvious advantages over other more traditional monitoring systems. However, there is an apparent shortage of applicable specifications and standards as well as reliable data processing techniques. The common interface between surveyors carrying out field data collection and their structural engineering counterparts who are responsible for further structural dynamic interpretation is far beyond mature. Structural engineers now still cannot fully understand the potentials of GPS and confidently use it as a major field data acquisition tool. Based on more than ten years experience in using GPS and other sensors such as triaxial accelerometers and ground-based pseudo-satellites for structural deformation and deflection monitoring in the UK, the authors present a feasible and reliable monitoring system and relevant data processing techniques which can be employed to monitor and analyse the performance of an operational suspension bridge with main spans varying from several tens of metres to more than one thousand metres. Detailed procedures for field data collection, data analysis and visualisation, generation of reliable analytical model, model updating and prediction for structural operational condition are also recommended. Data from a real-life bridge monitoring practice are analysed in the paper to address different issues raised by the authors.

1. A Brief Introduction to the Activities of the IESSG, The University of Nottingham in GNSS for Bridge Deformation Monitoring

Bridges are designed to withstand various forces, such as wind, traffic, temperature, tidal current and other extreme loadings, for instance, earthquake, flood and typhoon. These forces are the major affecting factors to be considered in bridge design and they govern in part a bridge's performance and life expectancy. Unlike long-term settlement of the bridge foundations, which can be easily monitored with periodic survey and using conventional surveying instruments such as a total station, the dynamic deformation behaviour or deflection of a bridge has been of great concern to civil engineers for many years due to its transient characteristic and sometimes it is difficult to be gauged [1]. A continuous monitoring of the structure is indispensable to ensure traffic safety and structural soundness. Monitoring of structural dynamics can also help reveal the real performance under severe loadings, which can provide extremely useful information for improving future design code [2].

With a well distributed satellite constellation and an open observation condition, geodetic type of dual frequency Global Positioning System (GPS) receivers can produce continuously cm level three-dimensional (3D) positioning accuracy. Moreover, GPS positioning characterises long-term stability, full automation, all weather observation and absolute measurement outputs. It has been proved as a viable technology for monitoring man-made structures, particularly useful for long bridge while other sensors such as an accelerometer might fail to work properly [3]. Through measuring instantaneous structural response with an array of GPS sensors installed on an operational bridge, structural dynamics, such as its natural frequencies, damping ratios and mode shapes can be obtained.

Like any other technology, GPS has its inherent limitations. For instance, to enable a GPS receiver on a bridge to carry out precise positioning, clear line of sight to a minimum of five well distributed satellites and one or more reference receiver(s) at a nearby location(s), with precisely known coordinates, are required. However, this observation condition cannot always be met in the context of bridge deformation monitoring. Weak signals from GPS satellites can be obstructed or reflected by any superstructure, surrounding topography, or even passing vehicles and this makes the direct interrogation of structural dynamics from the noisy output (normally in the form of continuous 3D coordinates and/or velocity time series) very difficult. Residual tropospheric signal delay caused by the significant height differences between bridge towers and reference/monitoring stations also limits positioning accuracy. For detecting high structural dynamics, slow sampling rate of current GPS receivers is inadequate for monitoring medium size bridge of several hundred metres. However, as discussed by Meng (2002), an accelerometer cannot reliably detect slow movements of a long span bridge. Streaming positioning solutions in a real-time kinematic (RTK) positioning mode from each monitoring node on the bridge deck to a control centre for further analysis or updating of a Finite Element (FE) model and diagnosis of the bridge performance is a very important function requirement of the monitoring system. However current hardware design of RTK GPS only allows one-directional communication which means after receiving corrections from reference station(s) for precise positioning on-deck GPS receivers cannot stream the fixed positioning solutions via same communication link.

The Institute of Engineering Surveying and Space Geodesy (IESSG), The University of Nottingham in the UK, has initiated the research on RTK GPS for structure deformation monitoring in the early 1990s [4]. Previous research focus was on the feasibility aspect of GPS technology. Further work in this area indicated that the development of integrated sensor systems and advanced signal processing is crucial [5 and 6]. This latest research evolved to a recent grant awarded by the UK's Engineering and Physical Sciences Research Council (EPSRC) under its structural integrity programme. The project was completed in the end of 2004. One of the major objectives of this project is to undertake the research necessary to set up a prototype remote bridge health monitoring system using an array of GPS sensors placed on an operational bridge to monitor its health condition without on-site inspection. Aimed at increasing the integrity and reliability of the whole monitoring system, hybrid sensor/software integration approaches have been investigated during the course of this research [3 and 6]. Algorithms for GPS error mitigation or reduction have been extensively developed and employed in practice [7 and 8]. An open Internet based positioning data streaming technique has also been developed and successfully integrated into previous monitoring system [9].

In this paper the authors present a feasible and reliable configuration of a monitoring system used in monitoring different type of bridges. It is followed by a discussion about what kind of expectation a civil engineer has for analysing structural performance. Detailed procedures for field data collection, data analysis and visualisation are also introduced. Real-life data from a case study bridge are analysed and cited as examples in the paper to address different issues raised by the authors.

2. Integrated Monitoring Systems for Bridge Deformation Monitoring

Over the years practice the performance of different vendors' GPS receivers have been tested but major receivers are from Leica. For the latest Leica dual frequency 1200 GPS receivers sampling at 20Hz the internal positioning accuracy can be better than a couple of millimetres which is adequate for most applications in deformation monitoring of long suspension bridges. However, recent work in analysing 100Hz accelerometer data reveals higher than 10Hz vibration frequencies are possible for this type of bridge which means even with this state of the art positioning technology problem may still exist in the measurability of GPS only monitoring system. Attempt has even been made to use 100Hz Javad GPS receivers but this kind of receiver has difficulty in fixing integer ambiguity in a dynamic environment where initialisation is not feasible. Other option is to integrate a geodetic dual frequency GPS receiver with a triaxial accelerometer as discussed by Meng (2002) and Roberts et al (2003) to increase the total sampling rate and overcome the drawback of accelerometer in sensing low frequency vibrations. However, seamless synchronisation of GPS and accelerometer is a key issue for the success of this integrated system. Efforts have been made to use Pulse Per Second (PPS) signal of a GPS receiver to trigger the data acquisition of a triaxial accelerometer. Further analysis can then be carried out on these exactly synchronised measurements. The other benefit of this integrated system is the increase in system robustness when GPS signal is weak, blocked or distorted by surroundings and an accurate positioning solution is not available. However, if this is the case the ultimate positioning solutions reply on the last GPS fix and if the absence of this fix is too long then the whole system will crash. This happened when a recent Forth Road Bridge test was carried out and two nearby references failed to work at same time for nearly two hours. Even worst, the active stations of Ordnance Survey in Edinburgh area all stopped and the actual reason is still a mystery. To avoid this happening several ground based GPS-like or other types of transmitters can be used to improve the over all signal transmitter geometry and hence the positioning accuracy as discussed by Meng et al (2004) and Barnes et al (2005). More research is required for a more flexible and reliable integrated system in the aspects such as clock synchronisation, multipath mitigation and tropospheric delay.

3. General Expectations of Civil Engineers for GNSS Based Bridge Deformation Monitoring Practices

The results or responses measured by a deformation monitoring system can be used for the design verification, justification of structural maintenance cost and traffic management which are the major expectations of structural engineering community. In many cases, loadings or inputs such as wind, earthquake, temperature and live traffic loadings on a bridge are unknown or difficult to gauge. Only partial the responses of the structure in the formats of geometric displacements, accelerations, stress and strain, etc. can be measured by various sensors embedded or installed on the different components of the bridge. These responses are then used to interrogate bridge health condition through the comparison of the theoretical predictions and those interpreted from various field measurements by sensors. The whole procedure sometimes is called vibration-based damage identification or ambient vibration test [11]. The fundamental behind this approach is that the vibration responses are dependent on the structural parameters such as mass, damping and stiffness. Theoretically, changes in these parameters caused by damage or deterioration produce changes in the vibration responses of the structure such as vibration frequencies, damping ratios and mode shapes. GNSS has proved to be a good tool in measuring global deformation but will it be a viable tool to assess and pinpoint the location of any potential damage? How many GPS sensors are required to achieve this and where the sensors should be placed?

4. A Practical Example

The Wilford Bridge is a suspension footbridge over the River Trent in Nottingham. Built at the beginning of the 20th century, the Wilford Bridge is a 69m long and 3.7m wide suspension footbridge (Figure 1). The bridge is held up by two sets of suspension cables restrained by two massive masonry anchorages and its steel deck is covered by a floor of wooden slats. It is about 2.8km away from the main campus of The University of Nottingham and was extensively utilised as a testbed for the abovementioned EPSRC project. The locations of GPS sensors were determined through an Effective Independence-Driving-Point Residue (EFI-DPR) technique developed by the project partner, Cranfield University. An initial analytical FE model was also created by Cranfield University using field measured structural dimensions since no detailed drawings are available for the bridge and this model is then gradually updated with field GPS and accelerometer measurements [12].

Figure 1. Wilford Bridge over the River Trent in Nottingham, UK

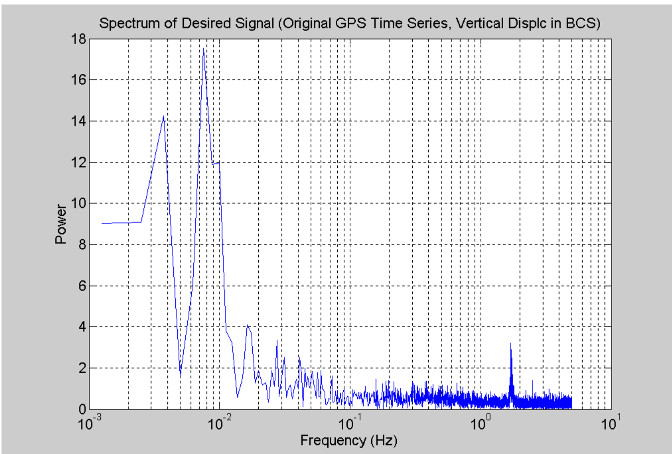

Figure 2. Comparison of the Spectrum of Multipath and Real Signal

Multipath is one of the major errors due to the signal reflection caused by surroundings and this effect can be significantly reduced using day-to-day repeating characteristic of GPS satellite constellation [8]. On the left side of Figure 2 the peak with a 2-minute period indicates spectrum of multipath and the small peak with about 1.73Hz period on the left side of the same graph shows the spectrum of the real bridge movement which is almost contaminated by the multipath signature and other noises. Through an adaptive filter, multipath can be effectively removed from the movement time series and these much cleaned data sets can then be used to validate an FE model. Figure 3 is the first four mode shapes of the Wilford Bridge generated with ANSYS software by Cranfield University.

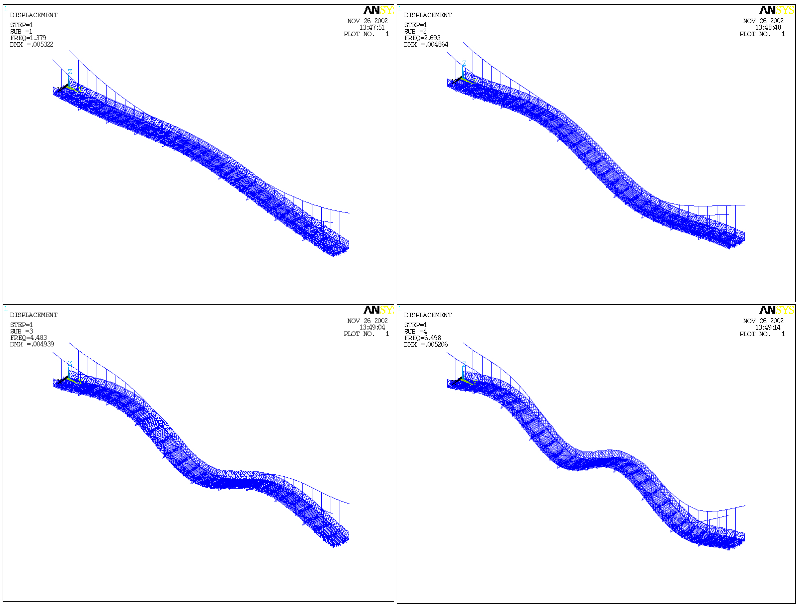

Figure 3. First Four Mode Shapes of the Wilford Bridge Developed with ANSYS® Software

First three structural vibration frequencies predicted by the FE model are listed in Table 1. To validate the developed FE model, band-pass filtering technique and Fast Fourier Transform (FFT) algorithm are employed to pick up vertical vibration frequencies from both GPS and accelerometer measurements and these estimated values are also listed in Table 1. It can be seen that the predicted values match very well with those of field measurements.

Model Frequency	FE Model (Hz)	GPS (Hz)	Accelerometer (Hz)
1	1.73	1.74	1.74
2	2.53	2.60	2.58
3	4.49	4.49	4.49

Table 1. Predicted and Estimated Vertical Vibration Frequencies (Hz) by and FE model and GPS and accelerometer

5. Conclusions

Even having been used for civil engineering more than one decade, GNSS based bridge deformation monitoring is still far from mature. Many challeging issues as briefly discussed in this paper need to be further investigated. In the paper, the authors demonstrate the potentials of an integrated systems for detecting bridge dynamics through a real-life example. It shows a precise FE model can be obtained through a series of model updating using field

GPS and accelerometer measurements and then employed to diagnose structural health conditions. The paper shows the predicted vibration frequencies match very well with those directly detected from field measurements which prove that the proposed monitoring system indeed can be used to monitoring structural dynamics precisely. Over the years, more trials have also been conducted by the authors on several long span suspension bridges such as the Humber Bridge and the Forth Road Bridge. Preliminary results can be found from IESSG's WWW site (www.nottingham.ac.uk/iessg).

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