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GPS deflection monitoring of the West Gate Bridge

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Abstract. The achievable precision and relatively high sampling rates of currently available GPS receivers are well suited for monitoring the movements of long-span engineering structures where the amplitude of movements is often more than a few centimetres and the frequency of vibrations is low (below 10 Hz). However, engineering structures often offer non-ideal environments for GPS data collection due to high multipath interference and obstructions causing cycle slips in the GPS observations. Also, for many engineering structures such as bridge decks, vertical movements are more pronounced and more structurally critical than horizontal movements. Accuracy of GPS determined positions in the vertical direction is typically two to three times poorer than in the horizontal component.

This paper describes the results of a GPS deflection monitoring trial on the West Gate Bridge in Melbourne, Australia. The results are compared to the estimated frequencies and movements from the design of the bridge and previous accelerometer campaigns. The frequency information derived from the GPS results is also compared to frequency data extracted from an accelerometer installed close to a GPS receiver. GPS results agree closely to the historical results and recent accelerometer trials for key modal frequencies. This indicates the suitability of GPS receivers to monitor engineering structures that exhibit smaller movements due to their stiffness and in environments not ideally suited to using GPS.

Keywords. West Gate Bridge, GPS, Deflection Monitoring, Accelerometers

1. Introduction

Many studies have been completed on the use of GPS for monitoring deflections of structures such as cable stayed bridges (Leach and Hyzak 1994, Larocca 2004), suspension bridges (Ashkenazi et al. 1997, Nakamura 2000, Wong et al. 2001), high rise buildings (Brownjohn et al. 2004, Çelebi 2000) and towers (Li et al. 2003, Lovse et al. 1995). Among these structures, bridges often present the most challenging environment for GPS data collection due to the presence of multipath signals from towers, cables and traffic. Multipath from reflected signals from stationary and near stationary objects like towers and cables repeats on a daily basis as the geometry between GPS receiver, reflectors and GPS satellites repeats. Its effect can thus be reduced by applying post-reception techniques like adaptive filtering (Roberts et al. 2002). Multipath arising from traffic, however, is nearly impossible to reject before signal reception or correct after reception. It is this *dynamic* multipath that often gives rise to high frequency noise in GPS positions in structural monitoring applications.

When monitoring large bridges, it is usually the vertical deflection of the deck that is the most critical element. Unfortunately this requirement does not sit well with the capabilities of GPS. The geometrical and physical limitations of using a satellite based measurement system mean that height is the weakest component of position, often being two or three times poorer than the horizontal component. Researchers have demonstrated that vertical accuracy can be improved by using Pseudolites [PSEUDO (-GPS-Satel)LITES] (Meng et al. 2004) but practical problems associated with their application to deformation monitoring exist and are under investigation (Dai et al. 2002). Moreover, since a pseudolite can act as a GPS jammer their use is becoming illegal in many countries including Australia (Australian Communication and Media Authority, 2004).

Despite the limitations mentioned above, experimental results have shown that GPS can be used to measure structural movements on large bridges, allowing the dynamic properties to be detected and the modal frequencies to be identified (Nakamura 2000, Roberts et al. 2000). This paper discusses the results of one such trial to validate the modal frequencies of West Gate Bridge in Melbourne, Australia using GPS.

The West Gate Bridge is a cable-stayed bridge where the amplitude of deck deflections is in the order of a few centimetres under ambient traffic and wind loading. In terms of monitoring this structure, practical considerations severely limit the choice of suitable locations for GPS antennas. The West Gate Bridge is therefore a challenging site for trialling GPS deflection monitoring.

In this paper, after a brief introduction to the bridge, an instrumentation scheme is described, which provides details of the different sensors used in the trial, their locations and configuration. The results from the different sensors are then graphed in both the time domain, in the form of displacements, and the frequency domain, in the form of Power Spectral Density (PSD) functions. As a result of this analysis, a number of modal frequencies have been observed in the PSD functions at different points on the bridge. Some of these frequencies were found to match or closely match results from earlier accelerometer investigations and model studies. Some other frequencies were observed for the first time. These findings are discussed in detail in this paper.

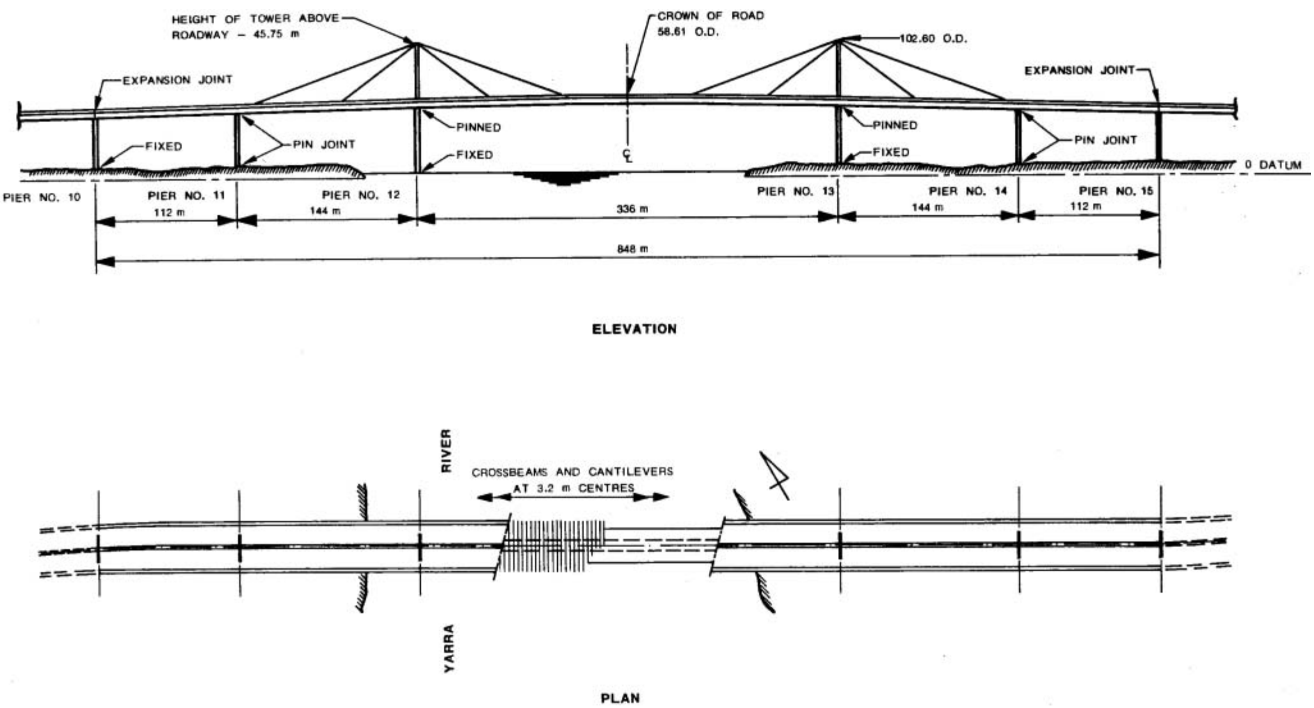


Figure 1: General layout of West Gate Bridge (source Balfe et al. 1986)

1.1. West Gate Bridge

The West Gate Bridge is a cable stayed box girder bridge constructed across Melbourne's Yarra River in the mid 1970s. The bridge was first opened to traffic in 1978. As well as being a prominent landscape feature, the bridge provides the primary vehicular link between the western suburbs and city's central business district. Estimated traffic volume is currently about 160,000 vehicles per day (Baker 2005). The West Gate Bridge consists of a number of steel spans with concrete approaches making a total length of 2,590 m. The central steel section of the bridge, as shown in Figure 1, consists of five spans of lengths 112 m, 144 m, 336 m, 144 m, and 112 m respectively. These spans are supported by a combination of cables and concrete piers. The two sets of cables are supported on steel towers, each rising to a height of 45.75 m above the deck of the bridge. The steel bridge deck is 58.61 m above the Yarra River and has a width of about 37.34 m. This deck width is achieved by welded cantilever beams on both sides of a trapezoidal box girder section.

2. Instrumentation

Four Leica System 500, dual frequency GPS receivers were used for the purposes of the trial reported here. Three of these receivers were coupled with Leica AT504 Choke Ring antennas, with a Leica AT502 antenna being used in conjunction with the fourth receiver. Ideally choke ring antennas would have been used with all receivers because of the potential for high multipath interference, but only three such antennas were available for the project. In addition to the GPS receivers, Four DYTRAN model 3191A uni-axial accelerometers were used for comparison and evaluation of the GPS results. These accelerometers have a sensitivity of 5 V/g and work in a frequency range of 0.1–1,000 Hz.

One GPS receiver with an AT504 antenna was installed close to the crown of the bridge in the median. The location of this receiver is labelled "CENTRE" in Figure 2 (photograph source URS Corporation Asia Pacific 2006). A second receiver with AT504 antenna was installed in the median near the quarter point of the central span and is labelled "EAST" in Figure 2. AT504 choke ring antennas were used with the receivers on the bridge deck to minimise the effect of multipath interference from different components of the bridge structure and from the high volume of passing traffic. A third GPS receiver with an AT502 antenna was installed on top of the eastern tower of the bridge and is labelled "TOWER" in Figure 2. The AT502 antenna was used for station TOWER because it was presumed that this highly elevated position would not be subject to significant multipath interference. The fourth GPS receiver and the final AT504 antenna were used as a base station, installed at a stable site on the roof of the nearby Science Works Museum, some 500 m from the bridge.

The antennas on the bridge deck at stations CENTRE and EAST were installed on purpose-built steel posts attached to the guard rail using timber spacers and bolts [see Figure 3 (a)]. These steel posts with a square base, when secured to the guard rails, were not expected to vibrate independently. Vibra-

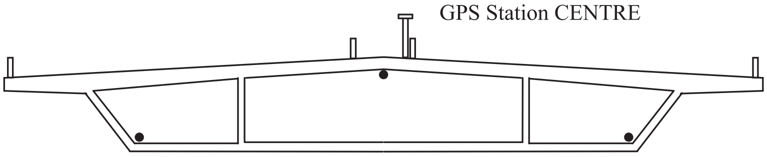
Figure 2: Location of GPS receivers on West Gate Bridge

(a) Station CENTRE & EAST (b) Station TOWER (c) Base station at Science Works

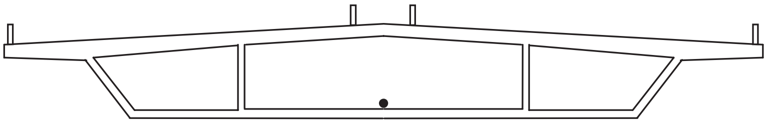
Figure 3: Installation of GPS antennas

tions of the guard rail, given its low height, are assumed to be of a high frequency and minimal amplitude. These vibrations, thus, will not affect the GPS determined positions and are ignored. The GPS receivers and controllers were stored in weather-proof boxes that were likewise secured to the guard rails. The antenna on the station TOWER was installed on a specially made magnetic base [see Figure 3 (b)]. The magnetic base was secured to the tower using cables to ensure it did not move or blow off in high wind conditions. The AT504 antenna for the base station receiver at Science Works was installed on a bracket that was permanently mounted on a concrete wall [see Figure 3 (c)].

Four accelerometers were used as part of the trial. Three of these accelerometers were installed inside the bridge deck immediately below station CENTRE [see Figure 4(a)]. One of this group of three accelerometers was installed on the longitudinal centreline



(a) Station CENTRE with the location of accelerometers shown as black dots



(b) Station EAST(A) with the location of accelerometer shown as a black dot

Figure 4: General layout of accelerometer installation for stations CENTRE and EAST(A)

on the ceiling of the steel section while the other two were installed on the floor at points as far as possible from the centreline. This arrangement was intended to identify any torsional modes in the modal analysis. The data collected from floor mounted accelerometers will not be used in the following analysis, but is the subject of another paper yet to be prepared. The fourth accelerometer was again installed inside the bridge deck on the floor at a point about 30 m east of station CENTRE. This accelerometer station has been labelled as "EAST (A)" in Figure 4(b). This station was intended to identify the frequency corresponding to 2nd anti-symmetrical vertical bending. All accelerometers were installed directly to the steel section of the bridge using their magnetic mounting bases. The data from accelerometers was fed to a signal conditioner, from where it was transmitted to a laptop PC for logging.

The installation of instruments on the West Gate Bridge is only possible during lane closures implemented for the purposes of routine maintenance works. Typically, such lane closures last 5–7 hours and occur on a regular though somewhat ad hoc basis. All the GPS receivers were installed during a lane closure on October 19, 2005 and left operating until the next lane closure on October 23, 2005 when they were collected and removed from the bridge. These were operated from 240 V power supply available on the bridge and at the base station. Data from the GPS receivers was stored on internal memory cards at a rate of 10 Hz. At this rate, the 256 MB cards reached capacity after approximately 40 hours of data collection. All GPS data was collected in a post-processed kinematic mode. Accelerometer data was collected during a single lane closure on February 15, 2006.

3. Results and discussion

3.1. GPS processing and bridge coordinate system

GPS raw data was downloaded and processed using the Leica Geomatics Office (LGO) software (version 1.0). The coordinates of the base station were first established by processing the base station data against data from a permanent GPS reference station operated by the Victorian State government (Land Victoria 2005). Data from the bridge GPS stations were processed in a kinematic manner using on-the-fly ambiguity resolution against data from the base station at 10 Hz. This resulted in epoch-by-epoch three dimensional coordinates in UTM Easting, Northing and ellipsoidal height for all stations, with ambiguities resolved for more than 99% of all epochs. Those few cases where ambiguities were not resolved were due to low common satellite counts.

The deck of West Gate Bridge is relatively stiff both laterally and longitudinally and is not expected to move significantly in either of these directions. The towers, however, will exhibit both lateral and particularly longitudinal movements. Deflections in the lateral direction will be smaller than in the longitudinal direction because the support at the base of the tower is fixed laterally but pin jointed longitudinally. To analyse the bridge movements detected by GPS in the lateral and longitudinal directions, the derived UTM coordinates were transformed into a de-facto Bridge Coordinate System (BCS).

Stations CENTRE and EAST were assumed to lie on a line parallel to the longitudinal centre line of the bridge. Average coordinates for these two stations were used to compute the azimuth of the centreline. A standard two-dimensional transformation with no translations and a unity scale factor was then used to transform the GPS derived Easting and Northing coordinates into the BCS. The transformation equation is given below:

$$\begin{bmatrix} Across \\ Along \end{bmatrix} = \begin{bmatrix} \sin\alpha & \cos\alpha \\ -\cos\alpha & \sin\alpha \end{bmatrix} \begin{bmatrix} Easting \\ Northing \end{bmatrix} \tag{1}$$

where "Across" and "Along" are components of bridge movement at right angles to and parallel to the bridge's longitudinal axis and "α" is the azimuth of the "Across" axis as shown in Figure 5.

3.2. Deflection analysis

Figure 6(a) shows vertical deflections recorded at station CENTRE over a period of about 3 hours on two

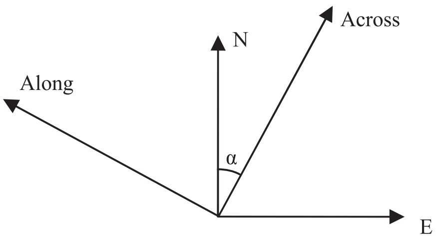
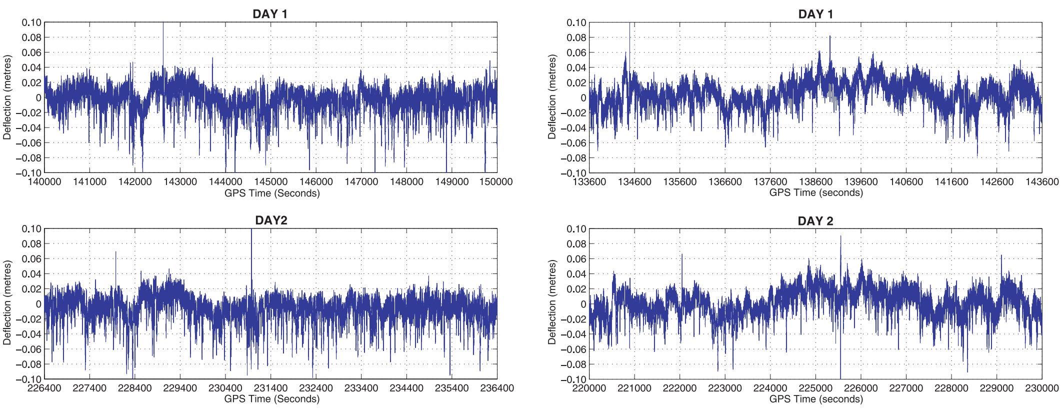


Figure 5: Transformation of GPS coordinates from MGA96 to BCS

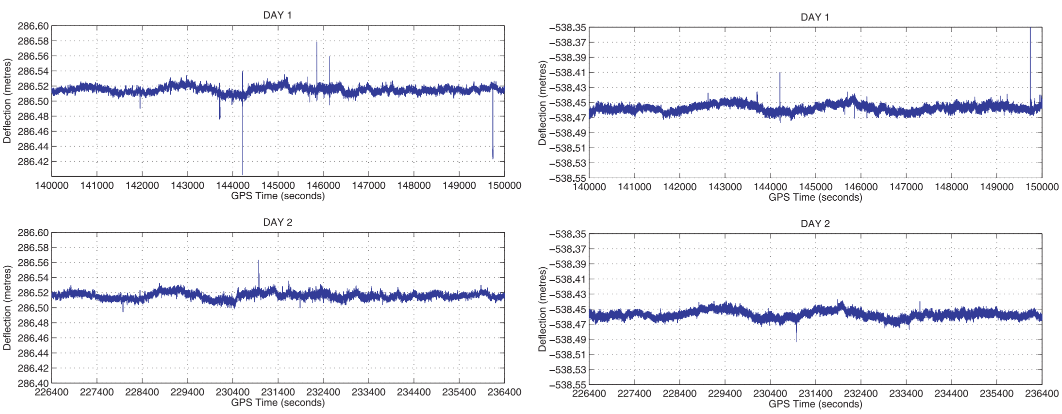
consecutive days. A number of high frequency outliers are present in both graphs. These outliers can be attributed to the influence of dynamic (non-repeating) multipath from passing traffic. There is also clear evidence of low frequency trends which are present and in both sets of data. The repetitive nature of these trends suggests that they are most likely the result of static (repeated) multipath caused by interference from the structure of the bridge itself with the GPS signals. Multipath mitigation techniques such as adaptive filtering have been shown to reduce the effect of repeated multipath interference in such environments (Roberts et al. 2002) but the application of such techniques is not in the scope of this paper. If the long-term trend is not considered, the thick band of positions can be taken to represent vertical bridge movements. This band is 3 cm thick on average, which is about the typical vertical accuracy of GPS positions. Similar trends of repetition and net deflections can be observed in the vertical deflections recorded at station EAST as shown in Figure 6(b). The number of high frequency outliers is less in this case and the daily repetition pattern of low frequency apparent deflections is more prominent reflecting the different multipath environment at the two stations.

The horizontal deflections along and across the longitudinal axis of the bridge deck are shown in Figure 7(a) and Figure 7(b) respectively for station CENTRE. The very low frequency effect of multipath interference, which repeats on a daily basis, is clearly visible in both plots. As expected, deflections along and across the bridge's longitudinal axis are minimal at sub-centimetre level. These apparent movements are the result of GPS noise as horizontal displacement of the bridge will be minimal. Looking



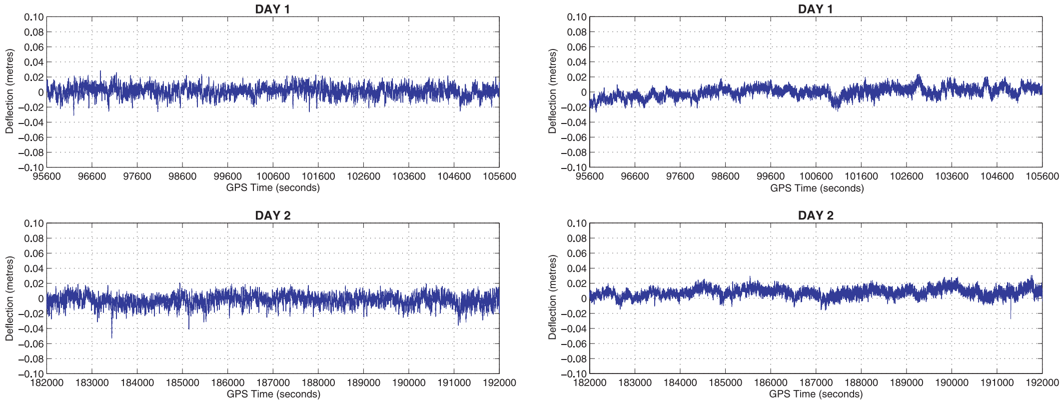
(a) Station CENTRE (b) Station EAST

Figure 6: Vertical deflections recorded at the bridge's deck



(a) Along the bridge's longitudinal axis (b) Across the bridge's longitudinal axis

Figure 7: Horizontal deflections recorded at station CENTRE on the bridge's deck



(a) Along the bridge's longitudinal axis (b) Across the bridge's longitudinal axis

Figure 8: Horizontal deflections recorded at the bridge's tower

closely at the results, deflections across the bridge's longitudinal axis are slightly more pronounced than along this axis. This can be attributed to slightly poorer satellite geometry in the north-south direction, keeping in mind that the bridge is roughly aligned along the East-West direction.

The horizontal deflections for a three hour period on two consecutive days at station TOWER along and across the longitudinal axis of the bridge are plotted in Figures 8(a) and 8(b) respectively. Low frequency daily repetition patterns caused by repeated multipath reflections are again evident in this data, though less prominent than in the previously discussed vertical deflection data for stations CENTRE and EAST. The net deflection along the longitudinal axis of the bridge in Figure 8(a) is around 1.5 cm, which is within the expected GPS precision in the horizontal direction. In Figure 8(b), across the longitudinal direction of the bridge the net deflection is around 1 cm, just in the detectable range for kinematic GPS.

3.3. *Frequency analysis*

Further analysis was conducted in the frequency domain of the GPS data and the accelerometer data collected at stations CENTRE and EAST(A). In this analysis, the dominant frequencies of bridge movements were determined using the Power Spectral Density (PSD) function of the GPS deflection time series and the raw accelerometer data.

PSD analysis of the GPS deflection data was done at 10 Hz, and using re-sampled datasets at 5 Hz and 2 Hz. Each dataset was divided into half hour blocks to allow the effect of outliers to be reduced. These outliers with high amplitude tend to bias the results of a PSD function. The PSD function of each dataset revealed dominant frequencies but the power of frequencies was a maximum for the 2 Hz datasets. Moreover, based on design information for the bridge (Balfe et al. 1986), all possible bending and torsional modes are expected to have frequencies of less than or equal to 1 Hz. Thus based on the Nyquist theorem, data sampled at 2 Hz is able to fully resolve the bridge dynamics. The 2 Hz GPS data is therefore used in the following analysis.

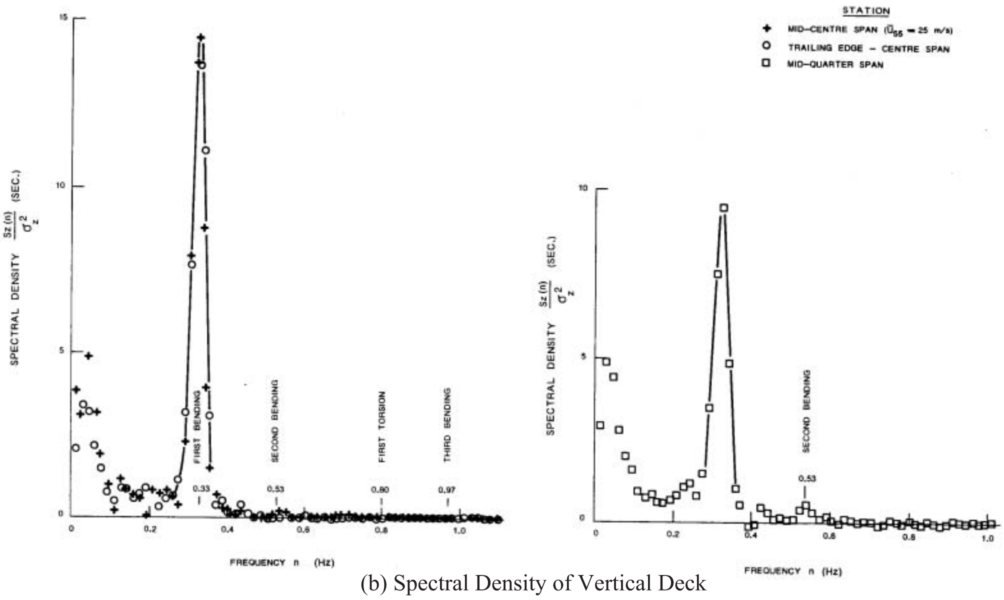
Accelerometer data was collected at a frequency of 256 Hz and used for PSD analysis at the same rate. This analysis is conducted using a dataset of 10 minutes (153,600 epochs), this being the longest continuous dataset collected by the accelerometers.

Dominant frequencies determined using the following PSD analysis will be compared to historical information about expected bridge behaviour. Figures 9(a) and 9(b) show a table and a pair of graphs sourced from Balfe et al. (1986) which summarise the expected bending and torsional frequencies for the bridge. These results were derived from wind tunnel tests on a bridge model and limited accelerometer data collected soon after the bridge was completed.

Figures 10(a) and 10(b) respectively show PSD functions derived from GPS vertical deflection and accelerometer time series data collected at station CENTRE. Comparing the PSD results to the expected frequencies given in Figure 9(a), it can be seen that a dominant frequency corresponding to the 1^{st} symmetrical vertical bending (0.34 Hz) has been clearly identified in both the GPS and the accelerometer data, though the GPS data is substantially more noisy. This measured value compares very favourably with the expected 1^{st} symmetrical bending frequency of 0.35 Hz. The accelerometer data also identifies dominant frequencies corresponding to the 3^{rd} symmetrical vertical bending (1.02 Hz, expected to be 1.00 Hz). Another dominant frequency identified by accelerometer is 0.785 Hz, which is close to the first torsional frequency derived from the bridge model study (0.80 Hz). This value, however, has been revised to 0.87 Hz for full bridge trials. This dominant frequency thus requires further investigations. These latter frequencies are hidden by noise in the GPS case, as the amplitude of the movements related to these frequencies is quite small.

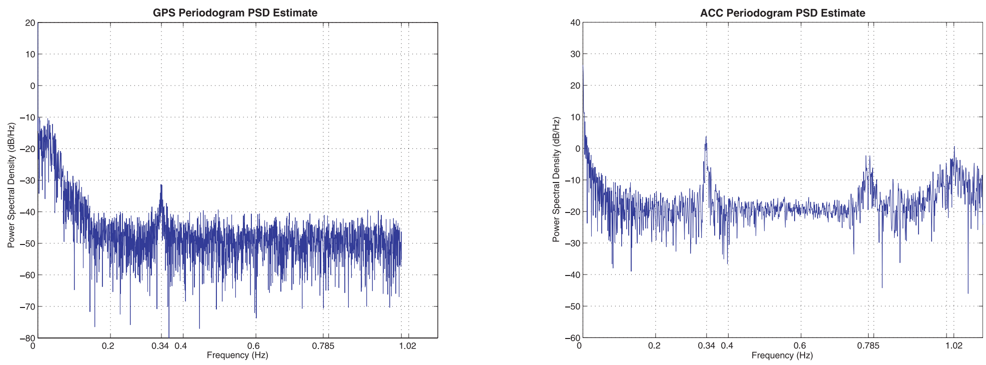
Mode	Frequency, n Hz		Full Scale Critical Damping Ratio, ζ
	Model	Full Scale	
FULL BRIDGE			
1st Vertical Bending (Symmetrical)	0.33 (LYCA analytical estimate 0.34)	0.35	0.009 (±1.8 mm to ±0.7 mm)
2nd Vertical Bending (Antisymmetrical)	0.53 (LYCA analytical estimate 0.55)	Not detected as yet	
3rd Vertical Bending	0.97	1.0	
S1st Torsion (Symmetrical)	0.80	0.87	0.003 (±0.006° to ±0.003°)
ERECTION CONFIGURATION JUST PRIOR TO CLOSURE			
1st Vertical Bending	0.30	0.38	0.012 (±3 mm to ±1.25 mm) 0.008 (±1.25 mm to ±0.75 mm)

(a) Natural Frequency and Damping Measurements



(b) Spectral Density of Vertical Deck Displacement Measured at Three Stations

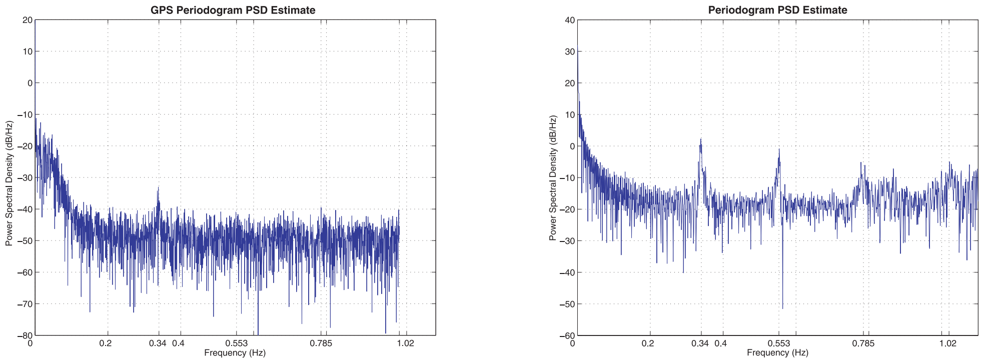
Figure 9: Summary of expected bending and torsion frequencies of West Gate Bridge



(a) PSD function of GPS vertical deflection time series

(b) PSD function of Accelerometer time series

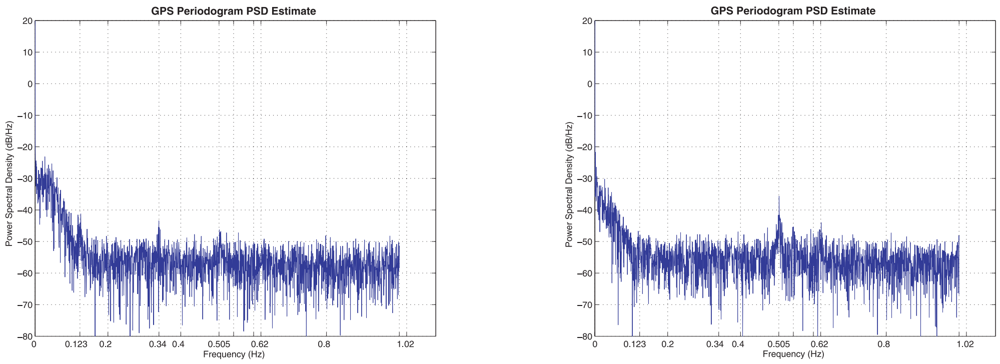
Figure 10: PSD functions of GPS and Accelerometer time series for station CENTRE



(a) PSD function of GPS vertical deflection time series on station EAST

(b) PSD function of Accelerometer time series on station EAST(A)

Figure 11: PSD functions of GPS and Accelerometer time series for station EAST & EAST(A)



(a) PSD function of GPS deflection time series along the bridge longitudinal axis

(b) PSD function of GPS deflection time series along the bridge longitudinal axis

Figure 12: PSD functions of GPS time series for station TOWER

Figures 11(a) and 11(b) show PSD functions developed from GPS vertical deflection and accelerometer time series data collected at station EAST and EAST(A) respectively. The only dominant frequency identified by the GPS deflection time series corresponds to the 1^{st} symmetrical vertical bending (0.34 Hz). The accelerometer on EAST(A), on the other hand, identified the same dominant frequencies as those detected by the accelerometer at CENTRE, in addition to another dominant frequency of 0.553 Hz, which closely corresponds to the 2^{nd} anti-symmetrical vertical bending [see Figure 9(a)]. This mode of movement in the bridge deck has not been detected in any earlier investigations on the completed bridge structure. The model study conducted during the bridge design phase predicted a value of 0.53 Hz for this bending mode. This frequency was not detected at CENTRE because this station is situated at the node of the mode shape for this frequency.

Figures 12(a) and 12(b) show the PSD functions developed from GPS horizontal movement data at station TOWER along and across the longitudinal axis of the bridge respectively. Accelerometers were not installed at this station. In the absence of any previous studies on the movement modes for the towers, it was assumed that frequencies corresponding to deck movements would be dominant in addition to the natural frequencies of the tower itself. From Figure 12(a), along the longitudinal axis of the bridge three dominant frequencies of 0.123 Hz, 0.34 Hz and 0.505 Hz were detected in the tower. As expected, the frequency of 0.34 Hz corresponds to the 1^{st} symmetrical vertical bending of the bridge deck. Further investigations are required to identify the nature of the other two dominant frequencies. In the across direction, shown in Figure 12(b), the frequency of 0.505 Hz is again present but with a higher power than in the along direction. Two other dominant frequencies at 0.545 Hz and 0.62 Hz are also observable and need further investigation.

Frequencies determined by GPS and accelerometers for different points on the West Gate Bridge along with frequencies determined from model studies and previous experiments are summarised in Table 1.

Table 1: Summary of bridge frequencies determined by GPS and accelerometers

Point on the bridge	Deflection Mode	Bridge model (Hz)	Full scale response (Hz)	GPS response (Hz)	Accelerometer response (Hz)
CENTRE	1st Vertical Bending	0.33	0.35	0.34	0.34
CENTRE	3rd Vertical Bending	0.97	1.00	Not detected	1.02
CENTRE	1st Torsion	0.80	0.87	Not detected	0.785
EAST / EAST(A)	1st Vertical Bending	0.33	0.35	0.34	0.34
EAST / EAST(A)	2nd Vertical Bending	0.53	Not detected	Not detected	0.553
EAST / EAST(A)	3rd Vertical Bending	0.97	1.00	Not detected	1.02
EAST / EAST(A)	1st Torsion	0.80	0.87	Not detected	0.785
TOWER ALONG[1]	Not Known	Not Known	Not Known	0.123	Not used
TOWER ALONG[1]	1st Vertical Bending[2]	0.33[2]	0.35[2]	0.34	Not used
TOWER ALONG[1]	Not Known	Not Known	Not Known	0.505	Not used
TOWER ACROSS[1]	Not Known	Not Known	Not Known	0.505	Not used
TOWER ACROSS[1]	Not Known	Not Known	Not Known	0.545	Not used
TOWER ACROSS[1]	Not Known	Not Known	Not Known	0.62	Not used

[1] ALONG and ACROSS mean along the longitudinal axis of the bridge and across it
[2] These correspond to the 1st vertical bending frequency of the bridge deck. The modal frequencies of the tower are not yet known

4. Conclusions

From the results discussed above, the authors have concluded that GPS can be used to monitor vertical deflections of the deck of the West Gate Bridge, despite the harshness of the environment in terms of multipath reflections from the structure itself and passing traffic. The results also demonstrate that GPS has successfully identified many of the dominant frequencies of the bridge, even though the amplitude of these deflections was hardly above the GPS noise level. Some new frequencies measured by GPS on the tower are yet to be attributed to appropriate modes of deflection. Future work will focus on the application of Adaptive Filtering for multipath mitigation in GPS results and confirmation of measured frequencies at station TOWER by accelerometer.

Acknowledgments

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References

Ashkenazi, V., Dodson, A. H., Moore, T., Roberts, G. W., Monitoring the movements of bridges by GPS, 10th International Technical Meeting of the Satellite Division of the Institute of Navigation, ION GPS-97. Part 2 (of 2), Kansas City, MO, USA, 1997.

Australian Communication and Media Authority, GPS jammers banned, Media Release No. 73-1, Sep 2004, http://www.acma.gov.au/ACMAINTER.1900810:STANDARD::pc=PC_1088, 2004 (last date accessed: Sep 2006).

Baker, R., West Gate review's revealing findings, News Article, The Age, Melbourne, http://www.theage.com.au/news/National/West-Gate-reviews-revealing-findings/2005/03/02/1109700538514.html, 2005 (last date accessed: Jan 2006).

Balfe, P. J., Jackson, A. B., Melbourne, W. H., Sewell, A. P., Toakley, A. R., Williams, D. G., Wolfram, H. G., Redesign of West Gate Bridge, Melbourne: Road Construction Authority Victoria Australia, 1986.

Brownjohn, J. M. W., Rizos, C., Tan, G. H., Pan, T. C., Real-time long term monitoring of static and dynamic displacements of an office tower, combining RTK GPS and accelerometer data, 1st FIG International Symposium of Engineering Surveys for Construction Works and Structural Engineering, Nottingham, United Kingdom, 2004.

Çelebi, M., GPS in dynamic monitoring of long-period structures, Soil Dyn. Earthq. Eng., 20 (2000), 477–483.

Dai, L., Wang, J., Rizos, C., Han, S., Pseudo-satellite applications in deformation monitoring, GPS Solutions, 5 (2002), 80–87.

Land Victoria, GPSnet GPS base station logon and site details, http://www.land.vic.gov.au/land/lcnlc2.nsf/alltitle/professions-geodesy-gpsnet-GPSnet+Logon+and+Base+Station+Site+Details, 2005 (last date accessed: Oct 2005).

Larocca, A. P. C., Using high-rate GPS data to monitor the dynamic behavior of a cable-stayed bridge, 17th International Technical Meeting of the Satellite Division of the U.S. Institute of Navigation, ION GPS / GNSS 2004, Long Beach, California, USA, 2004.

Leach, M. P., Hyzak, M., GPS structural monitoring as applied to cable-stayed suspension bridge, XX FIG Congress, Melbourne, Australia, 1994.

Li, X., Peng, G.-D., Rizos, C., Ge, L., Tamura, Y., Yoshida, A., Integration of GPS, accelerometers and optical fibre sensors for structural deformation monitoring, International Symposium on GPS/GNSS, Tokyo, Japan, 2003.

Lovse, J. W., Teskey, W. F., Lachapelle, G., Cannon, M. E., Dynamic deformation monitoring of tall structure using GPS technology, J. Surv. Eng. ASCE, 121 (1995), 35–40.

Meng, X., Roberts, G. W., Dodson, A. H., Cosser, E., Barnes, J., Rizos, C., Impact of GPS satellite and pseudolite geometry on structural deformation monitoring: analytical and empirical studies, J. Geodesy, 77 (2004), 809–822.

Nakamura, S. I., GPS measurement of wind-induced suspension bridge girder displacements, J. Struct. Eng. ASCE, 126 (2000), 1413–1419.

Roberts, G. W., Dodson, A. H., Brown, C. J., Karuna, R., Evans, R. A., Monitoring the height deflections of the Humber Bridge by GPS, GLONASS, and finite element modelling, in: Schwarz, K.-P. (Ed.), International Association of Geodesy Symposia, vol. 121, Springer, Berlin, Heidelberg (2000), 355–360.

Roberts, G. W., Meng, X., Dodson, A. H., Using adaptive filtering to detect multipath and cycle slips in GPS/Accelerometer bridge deflection monitoring data, FIG XXII International Congress, Washington, D.C., USA, 2002.

URS Corporation Asia Pacific, Our Business – West Gate Bridge Strengthening, http://www.ap.urscorp.com/_business/prjinx.asp?BDY=33, 2006 (last date accessed: Feb 2006).

Wong, K. Y., Man, K. L., Chan, W. Y., Monitoring Hong Kong's bridges: Real-time kinematic spans the gap, GPS World, 12 (2001), 10.

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