Further Results from Using GPS to Monitor the Deflections of the Forth Road Bridge

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Key words: deformation monitoring, GPS, frequency analysis.

SUMMARY

The Forth Road Bridge was built in 1962, and has a main span with a length of 1,005m long. GPS trials were carried out on the bridge by staff from the University of Nottingham in 2005, and a vast amount of GPS data was gathered. Initial processing and results have already been published, but this paper details further processing that has been carried out.

The new processing includes that of the towers, showing that they deform by up to 8cm with large traffic loading. Further to this, spectral analysis of the movements shows that there are indeed up to 5 frequencies that can be detected. The paper outlines the trials, as well as detailing the new results obtained.

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1. INTRODUCTION

The following paper details the ongoing research in deflection monitoring and deformation monitoring of structures, notably bridges. The use of kinematic GPS is being used for this and the work has been ongoing for about a decade at the University of Nottingham in collaboration with Brunel University [1], [2], [3]. It is possible to measure 3D deformations of discrete points upon the bridge at rates of up to 100Hz using GPS alone. It is also possible to measure sub-centimetre precisions over the short baselines used for this work. Typically the baseline lengths from the reference to rover receivers are approximately 1km or so.

Initial trials were carried out on the Humber Bridge and since then a number of trials have been carried out on other bridges including the Wilford Suspension Bridge in Nottingham, the Millennium Bridge in London and more recently the Forth Road Bridge in Scotland. During the trials, survey grade dual frequency GPS receivers are used, however, more recently research has also been carried out investigating the use of single frequency survey grade receivers (code and carrier) [4], [5]. Further to this, trials have been carried out investigating the use of cheap hand held GPS receivers as it is now possible to output the carrier phase from these receivers [6].

The work itself investigates the use of kinematic GPS as well as comparing this to the modelling of such structures. The overall aim is to be able to use a fixed number of GPS receivers located upon the bridge at pre-determined discrete locations and comparing the movements at these points with the FEM. Once agreement between the real data and the FEM established, then it is then possible to use the FEM to model how the remainder of the bridge moves based upon this real data.

2. THE FORTH ROAD BRIDGE GPS TRIALS

The Forth Road Bridge has an overall length of 2.5 km and a main span length of 1,005m. It was opened in 1964. Traffic has steadily increased over this bridge, from 4 million vehicles in 1964 to over 23 million in 2002. In addition, the heaviest commercial vehicles weighed 24 tonnes; the current limit is 44 tonnes. When the bridge was opened, it brought to an end an 800 year history of ferry-boat service across the river at Queensferry in Scotland.

The data gathering trials were conducted over a nearly continuous 46 hour period from 11am on the 8 February 2005 to 9am on the 10 February 2005. For the whole period, 7 GPS receivers were located upon the bridge, as illustrated in Figure 1, and two reference GPS receivers were located on the viewing platform adjacent to the FETA (Forth Estuary Transport Authority) building, Figure 2. The GPS receivers gathered data at a rate of 10Hz.

In addition, an Aplanix INS was located adjacent to point E [7]. The layout of the GPS antennas meant that a GPS antenna was located at each of the east side mid span, 1/4 span, 3/4 span and 3/8 span as well as the west side mid span and on top of the two southern towers. A selection of Leica SR530, SR510 and GX1230 surveying GPS receivers were used in conjunction with lightweight and choke ring GPS antennas.

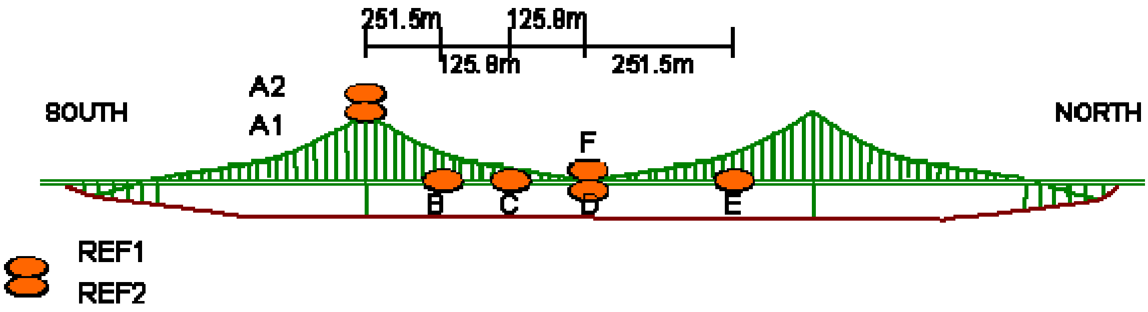

Fig. 1. Schematic of the Forth road bridge, and GPS receivers.

Fig. 2. Two GPS reference receivers located adjacent to the Forth road bridge (left). A GPS choke ring antenna attached to the bridge (right).

During the second night, two 40 tonne lorries were hired by FETA, accurately weighed and used as a control loading of the bridge. These trials were carried out a couple of hours after the high winds experienced subsided slightly, and during these specific trials the bridge was closed off to other traffic. The trials were carried out in the early hours of the morning, when the traffic flow over was at a minimum, and only closed whilst the control lorries passed over the bridge ad re-opened whilst they turned around before subsequent crossings. The lorries started the trials at the North end of the bridge, and the manoeuvres were as follows.

- 1 lorry ran from North to South
- 1 lorry ran from South to midspan on west side, stopped then the other lorry moved north to south
- 1 lorry moved from north to south and stopped at midspan, other moved south to north
- 1 lorry moved from south to north, and then both moved side by side north to south

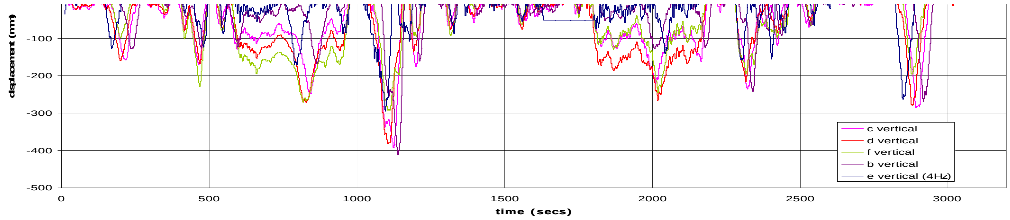

Fig. 3. Height Deflections of the Bridge During the lorry trials.

During these trials, the lorries travelled at 20 mph. Figure 3 illustrates the overall movements experienced by the bridge in the height component for the whole trials. The results show that the bridge deflected by up to 400mm, this is not due to the combined 80tonne loading, but happens when the bridge is opened to the waiting traffic following the controlled manoeuvres.

Figure 4 illustrates the final manoeuvre whereby the two lorries travelled from North to South whilst located side by side at 20mph. The graph also shows the physical location of the lorries at any time e.g. Midspan, North Tower etc

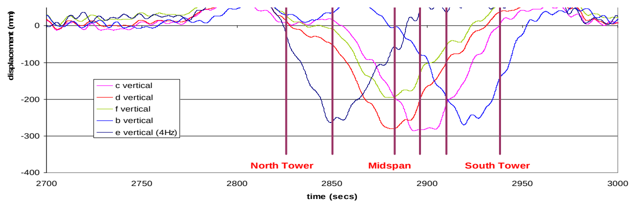

Fig. 4. Height deflections during the two 40tonne lorries passing over the Bridge side by side.

Three main phenomena are evident in Figure 4. Firstly the deflections are offset from each other. Secondly, the GPS receivers located at sites D and F, midspan, deflect by different magnitudes, even though they start off at the same height. This is due to the torsional movement of the bridge. The lorries, travelling on the left hand side of the carriageway from North to South, were in fact travelling on the East side of the bridge. Hence the eastern side (site D) deflects more than the Western side (site F). Thirdly, the reader should note that the bridge consists of three separate spans, each connected through a cable which passes over the top of the towers. As the lorries pass over the Northern side span, the load pushes this smaller span down, which in turn pulls the hanger cables down and the suspension cable which they are attached to. This then results in the suspension cable pulling up on the main span. This is evident in Figure 4 at around 2,800s. The lorries pass into the main span, and their passage over the measured positions are shown in Figure 4. As the lorries pass into the southerly side span, upward movement of the main span – described above – is observed.

3. NATURAL FREQUENCIES

Matlab's Fast Fourier Transform (FFT) algorithm was used to apply spectral analyses to the data gathered by each receiver so that the natural frequencies of the bridge deck and towers could then be identified. It has Already been mentioned that the 'north-south' movement of the tops of the towers corresponds with vertical movements of the bridge deck. Evidence for this can be seen in the Figures below. Referring back to Figure 1, Figures 10 and 11 show the vertical deflections of the receivers placed on the mid-span of the deck (receivers D and F) at 23:00 – 23:01 on 8th February. Figures 12 and 13 show the corresponding 'north-south' movement of the tops of both towers (receivers A1 and A2). It appears that when the height of the deck increases at both receivers on the deck, both receivers at the tops of the towers move 'south'. Hence it would be expected that a natural frequency identified on the bridge deck through spectral analysis would correspond with a frequency identified on the towers.

Two time periods were chosen in which to analyse the natural frequencies of the bridge: a quiet period at 02:00 – 03:30 hours on 9th February, and a period with heavy rush-hour traffic loading at 07:30 – 09:00 hours on the same day. The weather conditions for both periods, including both wind speed and direction, were very similar. A spectral analysis was applied to each session for each receiver. At this time, considering the formula frequency = √ (stiffness / mass) [8], it was thought that GPS may be able to detect slight decreases in natural frequency in the rush-hour period compared with the quiet period due to the increase in traffic loading.

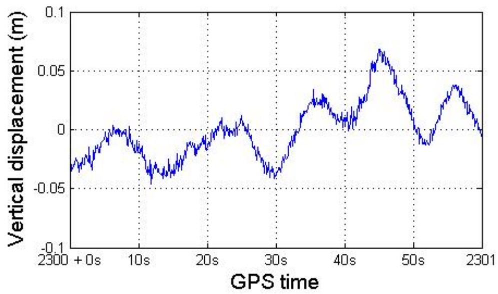

Fig. 10: Vertical displacement
Mid-span WEST (receiver F)

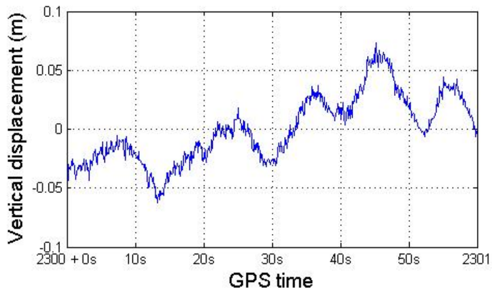

Fig. 11: Vertical displacement
Mid-span EAST (receiver D)

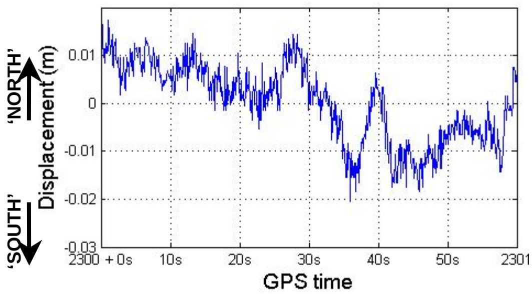

Fig. 12: 'North-south' displacement
Tower WEST (receiver

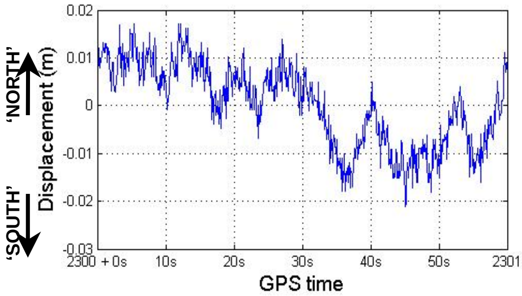

Fig. 13: 'North-south' displacement
Tower EAST (receiver A1)

As well as seeking the vertical and lateral frequencies of the bridge deck, the torsional frequency of the deck was also analysed. This was achieved by subtracting sample readings gathered by receiver F (mid-span, western side) from the corresponding samples gathered by receiver D on the eastern side. The resulting movement is shown below in Figure 14 which shows a very clear sinusoidal wave. This example is taken from the period 07:45 – 08:00 on 9th February. Figure 15 shows the corresponding spectral analysis, illustrating a clear torsional frequency of 0.27Hz.

In the same way the 'north-south' torsional movement of the towers was analysed by subtracting the data from the east tower with the data from the west tower. The resulting movement for 07:30 – 07:35 hours on 9th February is plotted in Figure 16. Again a sinusoidal wave is evident. The spectral analysis for all torsional movement between 07:30 – 09:00 on 9th of February is shown in Figure 17. The three peaks shown correspond to the frequencies 0.106Hz, 0.181Hz and 0.268Hz (see Table 2 below).

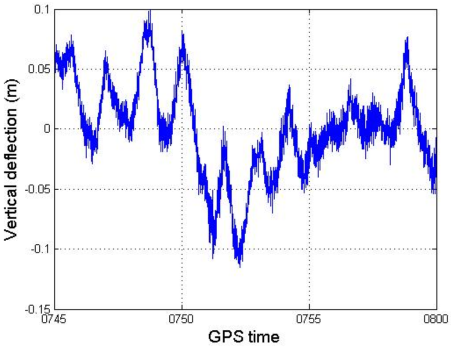

Figure 14: Torsional movement (Mid-span, vertical component)

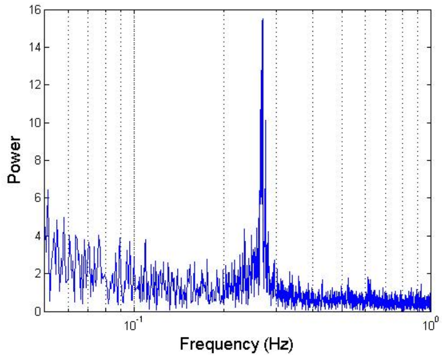

Figure 15: Spectral analysis of torsional movement

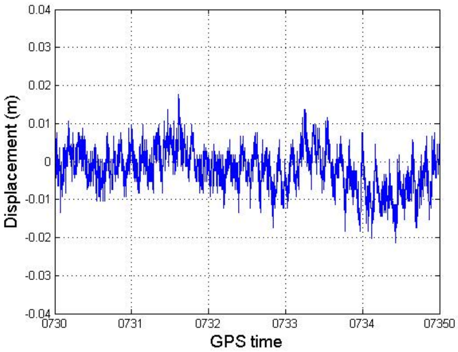

Figure 16: Torsional movement (Towers, ‘north-south’ component)

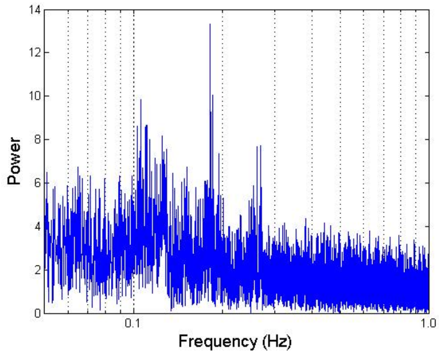

Figure 17: Spectral analysis of torsional movement

Results from the spectral analyses are summarised in Tables 1 and 2. All frequencies are given to four decimal places. The frequencies are printed in colour to highlight possible correlations.

02:00 – 03:30 9th February 2006		**Frequencies (Hz)**				
		First frequency	Secondary frequencies			
Mid span E	Vertical movement	0.1041		0.2069	0.2699	
	Lateral movement	0.0679			0.2689	
Mid span W	Vertical movement	0.1041		0.2057	0.2699	
	Lateral movement	0.0679			0.2689	
Mid span E & W	Torsional movement	0.2699				
3/8 span	Vertical movement	0.1040	0.1305	0.2069	0.2689	
	Lateral movement	0.0679	0.1773		0.2696	
1/4 span	Vertical movement	0.1041	0.1305	0.2005 ?	0.2699	0.4146
	Lateral movement	0.0673	0.1828			

Table 1: Frequencies detected through spectral analyses – 'quiet' period.

07:30 – 09:00 9th February 2006		**Frequencies (Hz)**				
		First frequency	Secondary frequencies			
Mid span E	Vertical movement	0.1026		0.2005	0.2684	
	Lateral movement	0.0668			0.2695	0.3424
Mid span W	Vertical movement	0.1026		0.2077	0.2684	
	Lateral movement	0.0668			0.2684	0.3424
Mid span E & W	Torsional movement	0.2684	0.6126			
3/8 span	Vertical movement	0.1027	0.1321	0.2077	0.2684	0.4160
	Lateral movement	0.0668	0.1781		0.2684	
1/4 span	Vertical movement	0.1027	0.1321	0.1938 ?	0.2684	0.4137
	Lateral movement	0.0668	0.1781			0.3294 ?

Table 2: Frequencies detected through spectral analyses – 'busy' period.

Looking at Tables 1 and 2, a number of observations can be made. The first natural frequencies of the bridge deck are 0.10Hz vertically and 0.07Hz laterally. These frequencies are easily identifiable at all receivers on the bridge deck. Also, the frequency of the vertical movement of the deck (0.10Hz) corresponds with the frequency of the 'north-south' movement of the top of the towers, as predicted at the start of this section.

The torsional movement of the bridge deck has a frequency of 0.27Hz, and this naturally corresponds to secondary frequencies identified in vertical and lateral movement at other locations on the deck since these are components of torsional movement. This frequency is detected in the movement (both 'north-south' and torsional) of the towers during the 07:30 – 09:00 period, but was perhaps too weak to be detected in the early morning period of 02:00 – 03:30 due to the lack of traffic to excite the bridge.

Tables 1 and 2 also show that the frequencies identified in the quiet period were also identified in the busy 'rush-hour' period, almost without exception. More secondary natural frequencies were identified in the busy period, again due to the increased agitation to the bridge deck by the traffic. However, such new frequencies were generally found to be quite weak.

The Tables also suggest that the natural frequencies identified during the rush-hour period are very slightly lower than in the quiet period, and this is the reason why the frequencies the Tables 1 and 2 are stated to four decimal places. For example, the first vertical modal frequency of the bridge deck was consistently identified as 0.104Hz in the quiet period and 0.103Hz in the busy period. The first modal frequency of lateral movement is identified as 0.068Hz in the quiet period (except at 1/4-span) but as 0.067Hz in the busy period. Even the secondary frequencies in the tower movement change from 0.151Hz / 0.154Hz in the quiet period to 0.148Hz in the busy period. Other examples, and some exceptions, can also be identified. Such small changes in frequency could be explained by the lack of frequency resolution in the spectral analysis, as discussed above, but the general lowering of frequencies between the two sessions could perhaps be due to the higher traffic loading during the rush-hour. Natural frequency is a function of both the mass and stiffness – a fact that would come naturally to any guitarist or violinist. Higher notes are produced by tighter and thinner strings. In fact, frequency = $\sqrt{(\text{stiffness} / \text{mass})}$, [8] so, in the case of bridge monitoring, an increase in mass would yield a relatively small reduction in natural frequency. The small changes in frequency reflect the fact that the total mass of extra traffic during the rush-hour, which may amount to a few hundred tonnes, is relatively insignificant compared to the mass of the bridge itself, which is approximately 39,000 tonnes (Forthbridges.org.uk, 2006).

4. CONCLUSIONS

The trials have shown that it is indeed feasible to use GPS on such structures to measure the magnitude and frequencies of the bridge's deflections in 3-D. This is possible at a rate of up to 10Hz, and all the results are synchronised to each other. Although the trials were carried out in a post processing manner, it is possible to have carried out these trials in real time.

The results have been compared to a FEM of the bridges, and this could well be the basis of future bridge monitoring whereby real GPS data from specific points on a bridge are used in conjunction with FEM, or similar model, to assess the behaviour of a bridge. If the structure deteriorates over time or if any specific mishaps occur then these actions may well be picked up through the model and GPS data.

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