ANALYSIS OF THE GPS MONITORING RECORD OF THE FORTH ROAD BRIDGE IN SCOTLAND

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Abstract: An extensive GPS bridge deflection monitoring trial was carried out on the Forth Road Bridge in Scotland in February 2005. The data of five GPS stations located along the main span of the Forth Road Bridge were analysed. These data cover a period of approximately 46.5 hours, and consist of the longitudinal, lateral and altitudinal displacements of five monitoring stations on the bridge deck. The aim of this study was the investigation of the behaviour of the bridge under different loading conditions (traffic, wind, etc.). The data was filtered using a band-pass filter and then analysed in the frequency domain using both the Fast Fourier Transforms (FFT) and the Lomb Normalized Periodogram (LNP). The spectral analysis using the FFT revealed oscillation frequencies of 0.08, 0.275 and 0.34 Hz for the lateral direction, 0.10, 0.20 and 0.26 Hz in the vertical and 0.17Hz for the longitudinal direction. Further analysis with LNP led to similar results. Analysis in the time-frequency domain was also applied in order to specify not only frequencies but also the time intervals at which they occurred. A code in Matlab® programming language was used, based on the short-time Fourier transform. One more frequency of 0.41 Hz was obtained, apart from those identified from the spectral analysis. All statistically significant detected frequencies seem to be present over the whole time period examined. The results of this study are consistent by a previous analysis based on the FFT method.

1. Introduction

The Forth Road Bridge (Fig. 1) in Scotland was opened in 1964 and is still among the largest suspension bridges in Europe. Together with the approach viaducts it is over 2 ½ km long, while the central span covers a distance of more than 1 km.

In order to identify the response of the bridge to different loading conditions and its functionality after more than 40 years of operation, its oscillations were recorded using GPS for 46.5 hours and this monitoring record was subsequently analyzed. This is a technique that has proved successful for numerous other bridges and may contribute in the safety and reduction of the cost of its maintenance [1, 2, 3].

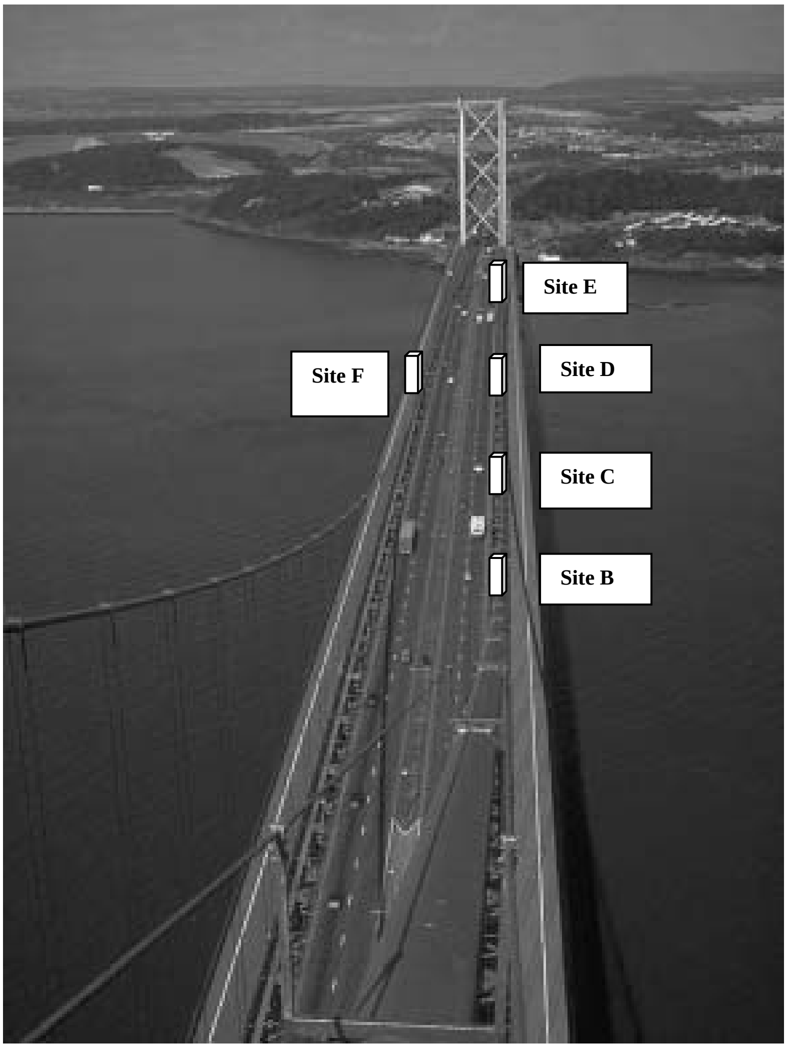

Figure 1: Plan-view of the Forth Road Bridge and the locations of monitoring stations B – F.

2. Available Data

Continuous GPS measurements of about a period of 46.5 hours at 10 Hz sampling rate from five monitoring stations (B – F) located along the main span of the bridge (Fig. 1) were recorded and analyzed. Using a linear transformation, coordinates of monitoring stations were first transformed to a local coordinate system with axis y parallel to the longitudinal axis of the bridge (Fig.2). Five data files were hence formed, one for each one of the monitoring stations. Each data file consists of more than 160000 sets of 1 Hz re-sampled coordinates of the corresponding monitoring station *i* at a specific moment.

The available data were oscillatory both because of the presence of wind and traffic on the bridge, but also of the GPS errors [4] i.e. multipath effect, ionospheric delay, etc. introduced during the measuring procedure.

Gaps, different in duration, up to 4295 sec, were also detected in the available data sets. Gaps were mostly due to the time needed to download the data and restart the measuring procedure and also other unspecified factors.

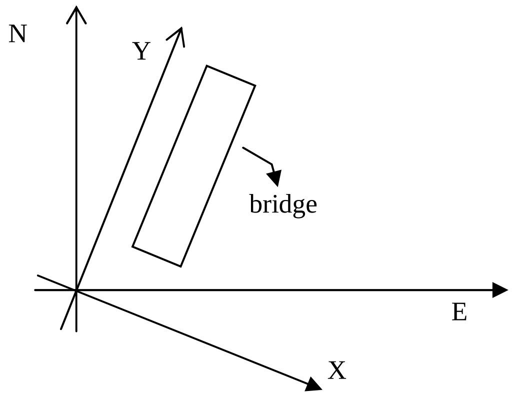

Figure 2: Sketch for coordinate transformation.

3. Methodology

Available data were analysed in three steps in order to denoise data, identify periodicities, as well as possible changes in the dynamic characteristics of the bridge versus time.

At a first step, a band-pass filter of 8^{th} order was used to filter out the noise contained in the data sets. The low-cut off-frequency was set equal to 0.05Hz and the high-cut off-frequency was set equal to 0.49 Hz.

At a second step and in order to detect possible periodicities in the available data, spectral analysis techniques, namely Fast Fourier Transforms (FFT) and the Lomb normalized periodogram (LNP) were applied.

In order to identify the frequencies hidden in the data, spectral analysis was applied. The most common technique in spectral analysis is FFT [5, 6, and 7]. Because of the requirement of the method for equidistant data, FFT was only applied to data sets consisting of evenly spaced values.

For comparison, Lomb normalized periodogram was also used [10 and 11]. This last algorithm is equivalent to the fitting of a sine curve to the data using the Least-Squares method and does not require equidistant data. In our analysis the “Normperiod code” [8 and 9] was used.

At the third step, and in order to detect the time intervals at which dominant frequencies detected in Step 2 are present and thus shed some light on possible changes in the behaviour of the bridge versus time, we applied a time-frequency analysis.

The spectrum obtained from the frequency analysis can reveal which frequencies are present in a signal, but it provides no information as to when those frequencies occur. In order to describe how the spectral content is changing over time several techniques can be used. These techniques decompose a function into a concentration over the time-frequency plane and are commonly known as time-frequency methods. Our analysis was based on the Short Time Fourier Transform (STFT) and a code developed for this purpose in Matlab programming language was used.

4. Data Analysis and Results

4.1. Spectral Analysis

Spectral analysis (FFT and LNP) was applied to the data. FFT was applied to denoised data sets consisting of up to 44760 evenly spaced values. LNP was applied to raw data. The number of values in the data sets used in this case was 164770. Table 1 summarises the results.

The FFT spectrum for the longitudinal direction was quite noisy with no obvious peaks except the one corresponding to 0.17 Hz.

The results obtained from the Lomb periodogram led to similar with the FFT results as it concerns the frequencies <0.1 Hz. No frequencies above that value were possible to be detected using this approach in none of the three directions. One reason may be the fact that the data used were not previously filtered, for this data does not correspond to the requirement of the filtering method for evenly spaced values. However, Lomb method could be applied even in such a case.

# of frequency	FFT frequencies (Hz)			LNP frequencies (Hz)		
	lateral direction	longitudinal direction	altitude direction	lateral direction*	longitudinal direction*	altitude direction*
1	0.08	0.17	0.1	0.07	-	0.1035
2	0.275	-	0.08	-	-	-
3	0.34	-	0.26	-	-	-
4		-	0.2	-	-	-

Table 1: Frequencies detected by the application of the FFT and the LNP method.
[*frequencies corresponding to peaks above the 99% significance level. Peaks detected at low (0-0.05Hz) frequencies were considered as noise (“edge effect” [5])

4.2. Time-frequency Analysis

Denoised (Step 1) data sets consisting of up to 44762 equidistant values were used in the analysis.

A code was developed specifically for this type of analysis using Short Time Fourier Transforms (STFT) in Matlab programming language. It contains a Matlab® function that uses the movement data, corresponding time values, values for the window length, length of the FFT and overlap, low pass and the high stop frequencies, the order of the filter used and the sampling rate as the inputs. The output is the STFT spectrogram.

After a number of trials the following values were found to be optimum for performing the STFT to the data: window length equals to 256, FFT length equals to 1024, and overlap equals to 230. Using a narrower window, the obtained resolution was better for the time domain but not for the frequency domain. The above combination of parameters provided us a satisfactory resolution for both frequency and time domain.

Data sets used for the application of the STFT were formed by selecting all values between consecutive gaps. Each data set was of different length, sometimes too short (<1000 values) to provide a clear spectrogram. The noise contained in the data was limited by the use of the band-pass filter but was still present corrupting the resolution of the results.

Most of the frequencies detected were the same for all control stations, especially for the movements along the altitudinal direction. It was found that frequencies common (to all control stations at all Sites (B – F)) were present over the whole time interval examined, although with a different amplitude and intensity from time to time. Table 2 summarises the results of the time frequency analysis.

Site	**Frequency (Hz) in 3 directions**		
	lateral	**longitudinal**	**altitude**
B	*0.085*	*0.085-0.16*	*0.1*
	0.175		0.135
	-		*0.2*
	-		*0.26*
	-		0.42
C	*0.085*	*0.085-0.16*	*0.1*
	0.175		0.135
	0.275		*0.2*
	-		*0.26*
D	*0.085*	*0.085-0.16*; 0.13 – 0.15 after 3pm on Wed. 9th Feb.	*0.1*
	0.275		*0.2*
	0.34		*0.26*
E	*0.085*	*0.085-0.16*	*0.1*
	0.175		0.135
	0.34		*0.2*
	0.41		*0.26*
	-		0.42
F	*0.085*	*0.085-0.16* ; 0.13 – 0.15 after 3pm on Wed. 9th Feb.	*0.1*
	0.275		*0.2*
	0.34		*0.26*

Table 2: Frequencies detected by the use of STFT in the data sets of the movements in all three directions (lateral, longitudinal and altitude) for all monitoring stations (B – F) located along the middle span of the bridge. [Values in italics are common in all Sites]

5. Discussion – Conclusions

The GPS record of five monitoring stations located along the middle span of the Forth Road Bridge was analysed using spectral and time-frequency analysis techniques.

The FFT analysis revealed 0.08, 0.275 and 0.34 Hz vibration frequencies for the lateral direction and 0.1, 0.2 and 0.26 Hz for the altitudinal direction. Frequencies for the longitudinal direction could not be safely interpreted. Results were consistent with those of previous work presented in [12].

The Lomb normalized periodogram led to results similar with these of the FFT for frequencies between 0.05 and 0.1Hz. Peaks at frequencies lower than 0.05 Hz were assumed to be not statistically significant.

Emphasis was given to the part of the analysis in the time-frequency domain. The results in Table 2 consist of the frequencies identified from the spectral analysis using the FFT and one new-detected frequency of 0.42 Hz.

The spectrograms obtained were, however, quite noisy in some cases especially for the longitudinal direction. The problem can be overcome by changing the width of the window during the analysis procedure. More specifically, try to adjust the band-pass filter used so that the frequency which corresponds to a detected peak in the previous loop is excluded from the next loop (peak and pick approach) and so on, and thus permitting the detection of a weaker peak.

The obtained resolution of the spectrograms did not permit to identify events such as heavy traffic. In particular, the effect of two heavy lorries crossing the bridge could not be identified through the plots. This is a challenge to be faced the future.

Acknowledgments

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