EXPERIMENTAL DETECTION OF THE PENANG BRIDGE VIBRATION WITH REAL TIME KINEMATIC GPS.

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Abstract

Vibration and dynamic deflection of bridge is an important aspect for bridge security evaluation. With the advance in sensor systems, data acquisition, data communication and computational methodologies, instrumentation-based monitoring has been a widely accepted technology to monitor and diagnose structural health and conditions for civil engineering structures such as bridges. For the health monitoring of bridges, sensors, which are reliable and robust, portable, non-destructive and automated such as Global Positioning System (GPS), are well suited. In addition, GPS also offer an opportunity for real or near real-time monitoring.

This paper reports on the first experimental realization of the bridge evaluation using real time kinematic (RTK) GPS technique through a series of tests conducted on the Penang Bridge. It gives details of the methodology and a strategy for detecting vibration of the bridge. This paper also focuses on applying frequency domain method to bridge vibration. Finally conclusions are drawn with regard to the feasibility of the GPS in a bridge vibration measurement.

Keywords:

Global Positioning System, real time kinematic, bridge,vibration.

1.0 INTRODUCTION

Vibration and dynamic deflection of bridge is an important aspect for bridge security evaluation. The security of a bridge is generally analysed by a comparison between the measured deflections and those determined from the load test. Due to the ageing of the bridge, increasing traffic and heavier loads as recommended by the standard have resulted in bridge engineers developing and using sensing and health monitoring technology for bridge assessment. For the health monitoring of bridges, sensors, which are reliable and robust, portable, non-destructive and automated such as GPS, are well suited. GPS also offer an opportunity for real or near real-time monitoring that may be able to detect structural failures. One of the first demonstrations of the potential for GPS to be used as sensors was done by *Leach and Hyzak* [1994]. They showed that GPS could be used as motion sensors to detect transient and long-term motions of a large cable-stayed bridge.

In recent years, a great deal of research has been conducted in the area of dynamic measurements of displacements of bridges using GPS, with the greatest interest lying in the use of RTK GPS [*Ashkenazi and Roberts*, 1997; *Duff and Hyzak*, 1997; *Ashkenazi et al.*, 1998; *Brown et al.*, 1999]. The development of RTK GPS technique has accelerated the progress on the use of GPS as sensors. Most of these research works are dedicated purely to aspects of achieving time history of dynamic response of bridges due to loading. Because GPS measurements are continuous and random, it can be analysed using the well-known time series technique. One area of research that has been of interest to GPS, as non-destructive sensor for bridge evaluation is frequency analysis method mentioned in this paper

The objective of this paper is to evaluate the performance GPS sensor and frequency analysis for structural monitoring of Penang Bridge in Penang, Malaysia. The bridge has been instrumented with GPS antenna during the heavy and low traffics and data sets were collected in real time. Finally, experimental results are presented.

2.0 Bridge Description: Penang Bridge

Penang Bridge is a cable-stayed type of bridge carrying the 6.2 km of dual carriageway and 2.2 km three lanes at the main span of the Seberang Prai on the mainland to Penang Island across the Penang Channel. It was the longest cable stayed bridge in Asia and the third longest in the world.

The bridge is shown in Figure 1 (looking from Gelugor). The typical dimensions of the bridge are as follows:

No. of spans:	533
No. of spans above water:	192
Main span	225 m
Total length	13.5 km

Figure 1: The Penang Bridge.

The bridge is made of prestressed and concrete cable stayed at the main span. There are four towers located on the main span at a height of 101.5 m above the water. Although the bridge was built to withstand earthquake of up to 7.5 Ritcher scale, it is affected by strong constraints caused by winds, traffic loading and temperature variations. Currently, The Penang Bridge Sdn Bhd (PBSB) manages the bridge and is responsible for managing, operating, upgrading and collecting toll from the bridge.

3.0 Experimentation and Data Processing

For the purpose of this experiment, two Leica GPS 500 dual frequency receivers with choke ring antennas were used on the 29th – 30th April 2003 to make observations in real time kinematic (RTK) mode. For this implementation, one receiver was configured as reference station and the other as rover. The reference station was located on top of the N-Park Condominium, approximately 1 km from the monitoring point on the bridge. This station was selected due to its height (approximately 100m) and the capability to transmit the differential signal to the rover. The stability of the reference point has been verified by connecting the station to two known points through GPS observation. These stations were part of the JUPEM GPS network. Between the 2 sessions, the coordinates of the reference on the roof did not change significantly.

To measure bridge deck displacement due to traffic loading, the second antenna was instrumented to the bridge at various emergency bay locations and the mid span of the bridge deck. For this reason, specially developed bracket were used to allow the antennas to be attached directly to the bridge deck (see Figure 2).

Figure 2: Monitoring Point.

Data was collected at a sampling rate of 1Hz for about 15 minutes during the time period of low and heavy traffic flows. Corrections generated at the reference station were communicated to the rover receiver through a telemetry link. Each emergency bay on the bridge deck and three points on the mid span were visited. In this paper, only the measurement recorded at the first monitoring point on the emergency bay and the middle span are presented.

4.0 Analysis of Results

The RTK processing was performed yielding time series of co-ordinates at an interval of 1 second. For each point, a total of 900 sample points have been measured for the first and second experiments. The antenna on the bridge deck was found to be orientated at an angle of 98.95 degrees to the true North. As the computed positions are referenced to the true North, for the purpose data analysis, they should be transformed to a local bridge co-ordinate system. With this new co-ordinate system, it allows the movement to be analysed in longitudinal (along) and lateral (across) directions. For this new co-ordinate system, the height component remains unchanged.

The transformed raw positions of the receiver installed at the emergency bay of the bridge in longitudinal, lateral and vertical directions are illustrated in Figure 3. Figures were plotted with respect to mean value and represent a record of measurement from

10:28 am to 10:43 am on April 29, 2003. The plots are dominated with high-frequency noise, which requires low pass filtering. The preliminary review of the plots that resulted from the experiment appeared to be agreed with the loading effect on the bridge. The bridge structure under study was influenced by the traffic loading, which caused vertical deflection and vibration. Wind loading is insignificant at this emergency bay and it can be verified from the slow wind speed measurement of 1.5 – 4 m/s during the time of observation. Wind speed data have been provided by the Bayan Lepas Meteorological Department. From the plots, we can see a correlation between lateral and height deflection. The maximum amplitude for longitudinal and lateral movement was ±2cm and an approximately ±5cm for height. Nevertheless, the plots are contaminated with noises, which should be filtered for example using low pass filter.

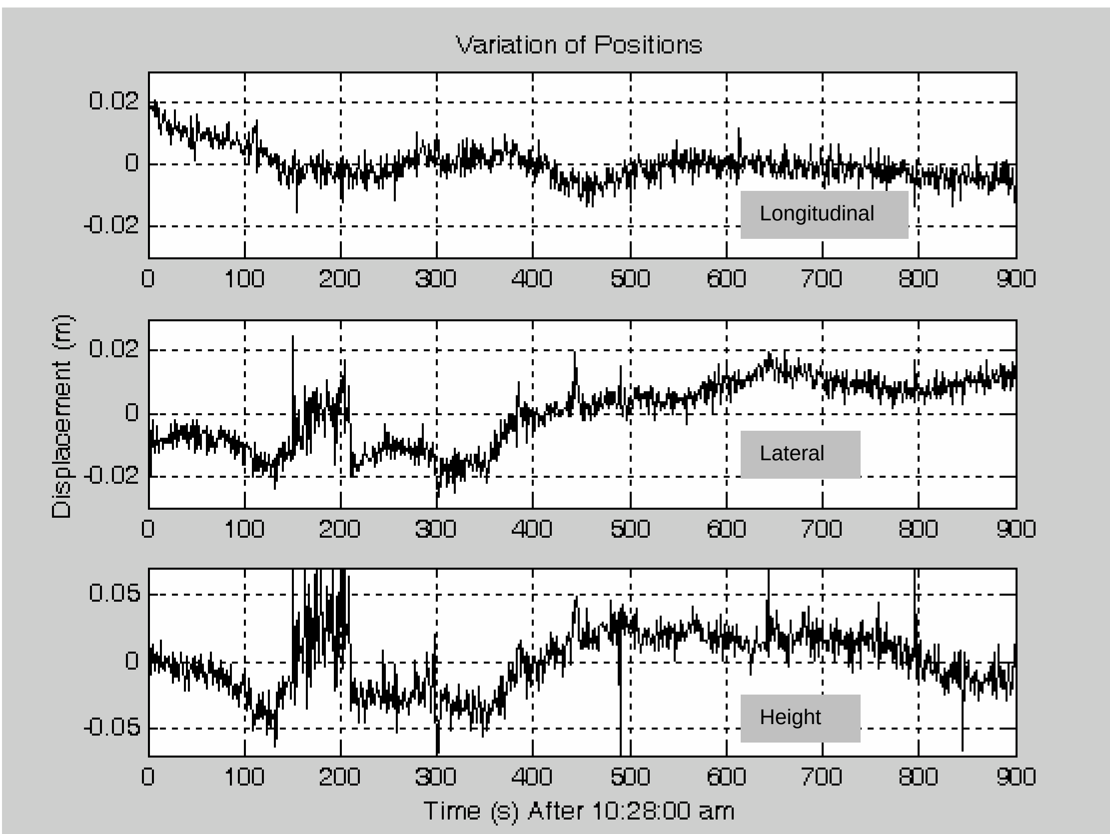

Figure 3: Variation of Positions on Bridge Deck

Rather than time series plots presented in Figure 3, alternatively, it is increasingly becoming more attractive to study time series in terms of repetitive cycles. For time series or signal, which have apparent periodicity such as in this study, it is possible to break down a series into its various frequency component using a set of analysis tools. This tool, decompose the series into its constituent parts by an infinite series of trigonometric functions, called a Fourier series (notably using the Fast Fourier Transform (FFT) technique) (Brigham (1974), Bendat & Piersol (1986) and Chatfield (1996)).

The Fourier transform decomposes or separates a waveform into sinusoids of different frequency, which sum to the original waveform. It identifies or classified the different frequency sinusoids and their respective amplitudes. The Fourier transform can also be perceived as a transformation or relationship between time and frequency domain representation of a process. If a time representation by *x(t)* and its frequency counterpart by *F(f)*, this relationship is given as

$$F(f) = \int_{-\infty}^{\infty} x(t) e^{-2\pi i f t} dt \tag{1}$$

$$x(t) = \int_{-\infty}^{\infty} F(f) e^{2\pi i f t} df \tag{2}$$

Equation (2) is called the inverse Fourier transform. In practice, discrete Fourier transform (DFT) is defined for a finite process of length *N*, sampled at a uniform sampling frequency. This can be expressed as

$$F(k) = \sum_{n=0}^{N-1} x(n) e^{-2\pi i k n . N} \qquad k=0,1,\ldots,N-1 \tag{3}$$

with the corresponding inverse transform

$$x(n) = \frac{1}{N} \sum_{n=0}^{N-1} F(k) e^{2\pi i k n / N} \tag{4}$$

Knowledge of the frequency content of the signal is very important for understanding its original representation and is required in the data analysis for this study. Other reason for seeking frequency content is concerned with the determination of the peak frequency, which can be used in visual interpretation of the data. The FFT amplitude of the time series for the bridge deck is shown in Figure 4. The figure exhibits a typical pattern for autoregressive model (or white noise), which mainly consists of low frequency components.

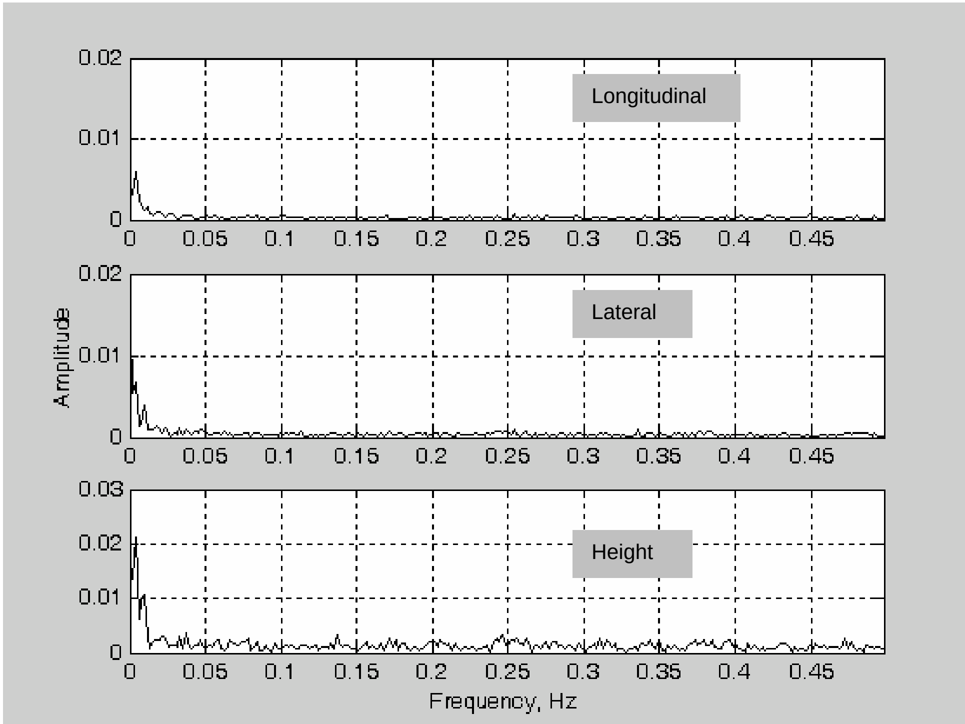

Figure 4: Spectrum of the Bridge Deck.

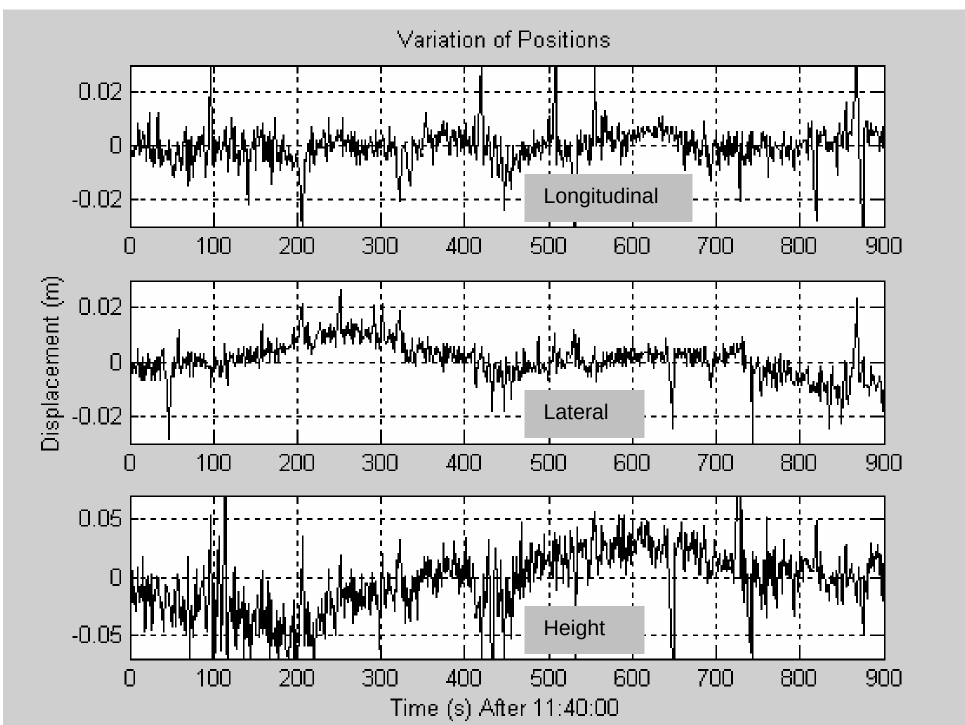

Figure 5: Variations of Positions on Cable-Stayed.

Fortunately, the existence of several natural frequencies in the spectrum and coupled with the understanding of Fourier series can give insight into an additional way of data interpretation. As mentioned earlier, the low traffic flow during the observation justified the non-existence of any obvious sharp burst in the frequency for height and other components.

In comparison to the bridge deck plots, Figure 5 is a plot of the highest point on the bridge i.e. at the mid span of the cable stayed. The figure shows the results obtained from the measurement executed on April 30, 2003. The trend shown in this figure was different to that of Figure 3 with occasional spikes, which correspond to cycle slips due to steel cables. The traffic was slightly low compared to that of Figure 3.

5.0 Conclusion

The Penang Bridge, which is subjected to traffic loading, has been investigated in this study. In the experiment, data was collected during the period when there was low and high traffic flow. The study has demonstrated the feasibility of GPS and frequency domain analysis technique to detect dynamic deflection of the structures. The test done on this technique has proven that it can provide solutions to structural monitoring and contributes toward efforts in the application of GPS as non-destructive evaluation technique for civil structures. Nevertheless, more research is still required to fully understand all sources of errors and their influences on GPS results.

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