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Tower Bridge Movement Analysis with GPS and Accelerometer Techniques: Case Study Yonghe Tower Bridge

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Abstract: This study investigates the possibility of using Wden Matlab function and Fast Fourier Transformation (FFT) method for bridge tower movement analysis. GPS and accelerometer techniques were used to collect the lateral displacements, acceleration and torsion displacements data of a Yonghe bridge tower. The analysis of test results indicate that the: (1) noise of GPS signals is high (2) signals accuracy obtained from the wden function increased by 20%; (3) traffic loads are the main factor affects the tower movement; (4) power spectral density is a good parameter to detect the tower movements and (5) GPS can be used as a trustworthy tool for characterizing the dynamic behavior of the low frequency bridges.

Key words: Bridge, Fast Fourier Transformation, GPS, accelerometer, movement

INTRODUCTION

Global Positioning System (GPS) with 10-20 Hz sampling rates has become a useful tool for measuring and monitoring static, quasi-static and dynamic responses in long-period civil engineering structures exposed to gust-winds, traffic, earthquakes or temperature variation. Accelerometers have been used extensively for bridge dynamic monitoring using the force measurements directly. These sensors are used to sense accelerations. Compared with other surveying systems such as a surveying total station, accelerometers have some special advantages when they are used for bridge monitoring. The sampling rate of an accelerometer can reach several hundred Hz or even higher depending upon application requirements, which is a very important characteristic when monitoring a bridge with high dynamics (Meng *et al*., 2007).

Loves *et al.* (1995) measured horizontal displacement history of calgary tower against wind loads using GPS and analyzed the natural frequency based on such measurements. Çelebi (2000) measured horizontal displacement history of a 44-story building and verified that the natural frequency of 0-23 Hz as computed from such measurement coincided with the natural frequency as analyzed from the building's accelerometer study. Tamura *et al.* (2002) demonstrated that it was possible to directly measure actual displacements using GPS with publicized accuracy of ±1 cm +1 part per million (ppm) in cases when a building's natural frequency is less than 2 Hz and amplitude greater than 2 cm and published the displacement history of a 108 m steel tower. Breuer *et al.* (2002) measured displacement history and natural frequency of the Stuttgart TV tower against wind loads and suggested the usefulness of GPS in monitoring safety of high-rise buildings that are thin and long based on such GPS measurements. But due to the inherent deficiency in the GPS satellite geometry, multipath, residual tropospheric delay and cycle slips, GPS alone cannot provide the required positioning precision all the time to meet the requirements for such a system to detect subtle deformations of structures (Meng *et al*., 2007). So Meng *et al.* (2007) and Chan *et al.* (2006) integrated GPS-measured signals with accelerometer-measured signals to enhance the measurement accuracy of total (static plus dynamic) displacement response of a structure.

The aims of this study are: (1) to use the wden function available within Matlab library to de-noise the GPS signals; (2) to examine the GPS and accelerometer techniques in deformation monitoring of the bridge towers; (3) to calculate the displacement and frequency of the bridge towers and (4) to evaluate the effects of the applied loads on the bridge tower movements.

BRIDGE DESCRIPTION AND DATA COLLECTION

The Yonghe Bridge links the two cities in China (Tianjin and Hangu). This bridge was constructed by pre-stressed concrete in December, 1987, closed in October, 2006 because of cracks over mid-span and

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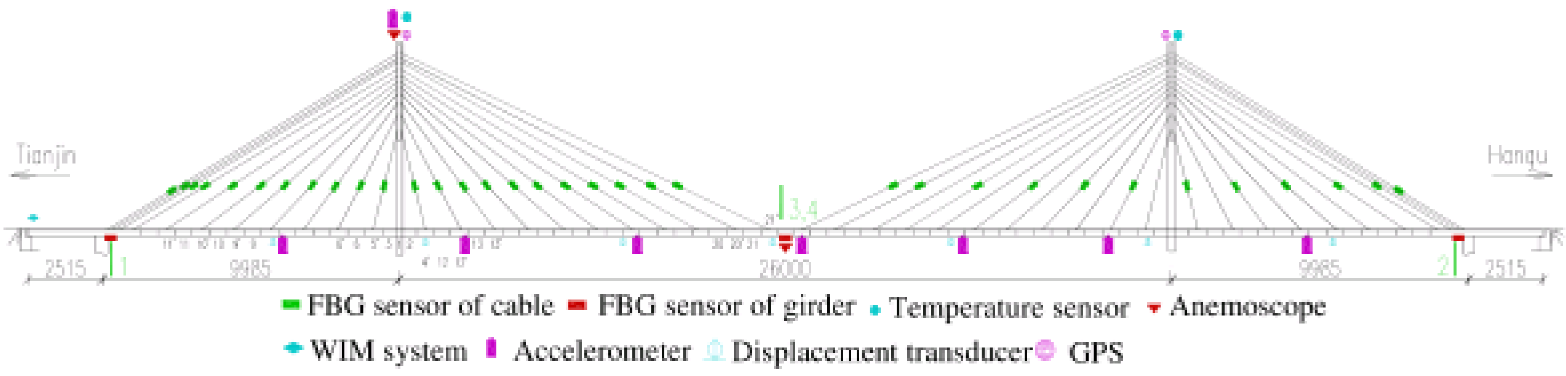

Fig. 1: Diagram of Yonghe Bridge and the position of the sensors

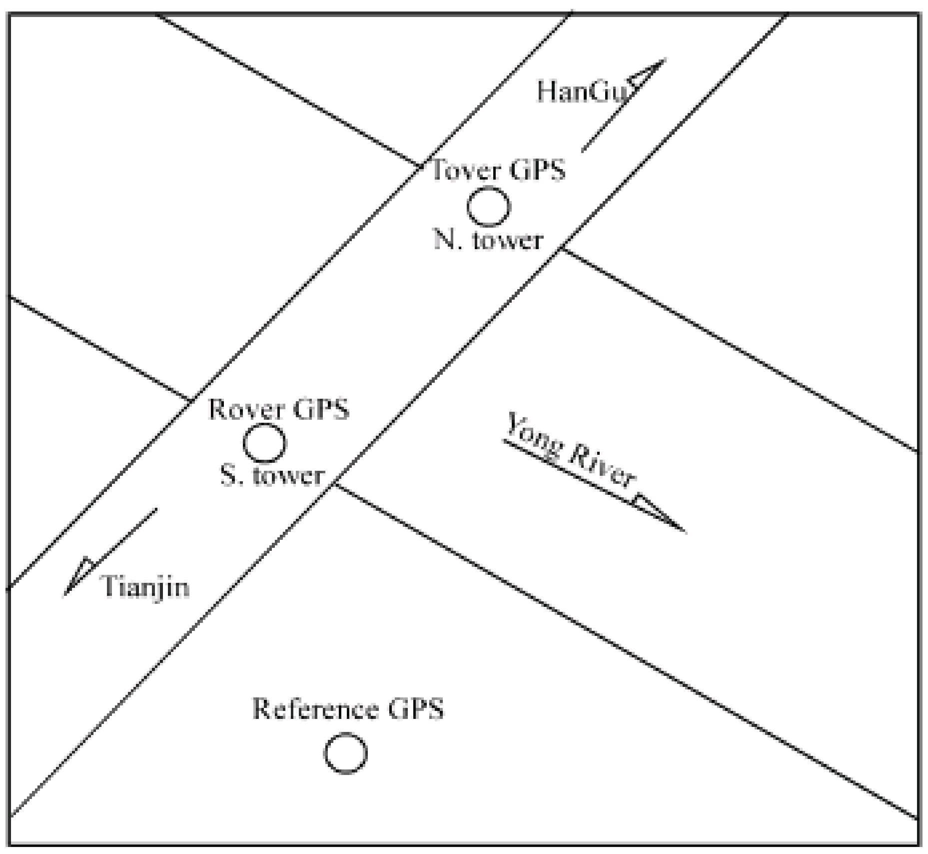

Fig. 2: GPS dynamic monitoring scheme

opened in August, 2007 after rehabilitation. The Yonghe Bridge has four lanes with the total length of 510.00 m and main span of the bridge is 260.00 m (Fig. 1). For safety assurance, a sophisticated long-term Structural Health Monitoring (SHM) system has been designed and implemented by the Research Center of Structural Health Monitoring and Control of Harbin Institute of Technology (HIT) to monitor loads and response of the bridge. The structural health monitoring system for the Yonghe Bridge comprises a data acquisition and processing system with a total of approximate 179 sensors, including accelerometers, strain gauges, displacement transducers, anemometers, temperature sensors, weight-in-motion sensors and three GPS's (Fig. 2). The GPS's were permanently installed on the two towers tops of the bridge and bank near the bridge. A local Bridge Coordinate System (BCS) was chosen for the analysis and evaluation procedures of the observations performed. In this coordinate system, the Y-axis shows the traffic direction (span direction), the X-axis shows the lateral direction and the Z-axis gives the vertical direction of the bridge. It was assumed that this coordinate system would be beneficial for the evaluation of performed observations, description of the movement of the structure and allow a better interpretation of the analysis results as it is related to the movement directions of the structure.

RESULTS

In this section, the data of South tower of Yonghe Bridge was collected in January 17 2008 from 12:00 to 13:00 p.m. The analysis was based on the data collection in the X and y-directions, since, the movement in these directions are greater than in Z-direction, thus the data in Z-direction were declined.

GPS displacement: For analyzing the signals of GPS measurements, a preprocessing should be done first. That is to delete noises and extract useful signals. Wavelet analysis is a strong tool to eliminate noises according to the noise characteristics. Function wden is exploited to eliminate noises of one dimension time series in Matlab wavelet analysis packet automatically. There are 4 kinds of method to select the threshold and soft, hard threshold eliminating noises. Furthermore, there are global or decomposed layers threshold available for selecting also. In this study, within the wden function, heursure is used to eliminate and compact the noises (Yu *et al*., 2006). Displacement measurements were performed on January 17, 2008 from 12:00 to 13:00 PM. The original displacement history measurements in X and Y directions (local coordinates) on the tower were extracted using wden function as presented in Fig. 3a and b. Time history of wind and temperature for the bridge is shown in (Fig. 4a-b).

The trend components in the series were investigated from the obtained data within wden analysis. The trend component in the series represents the long-term changes related to time and it can be defined by a polynomial function in the time domain. The transformation of the series without trend components from time domain to frequency domain is performed using Fast Fourier

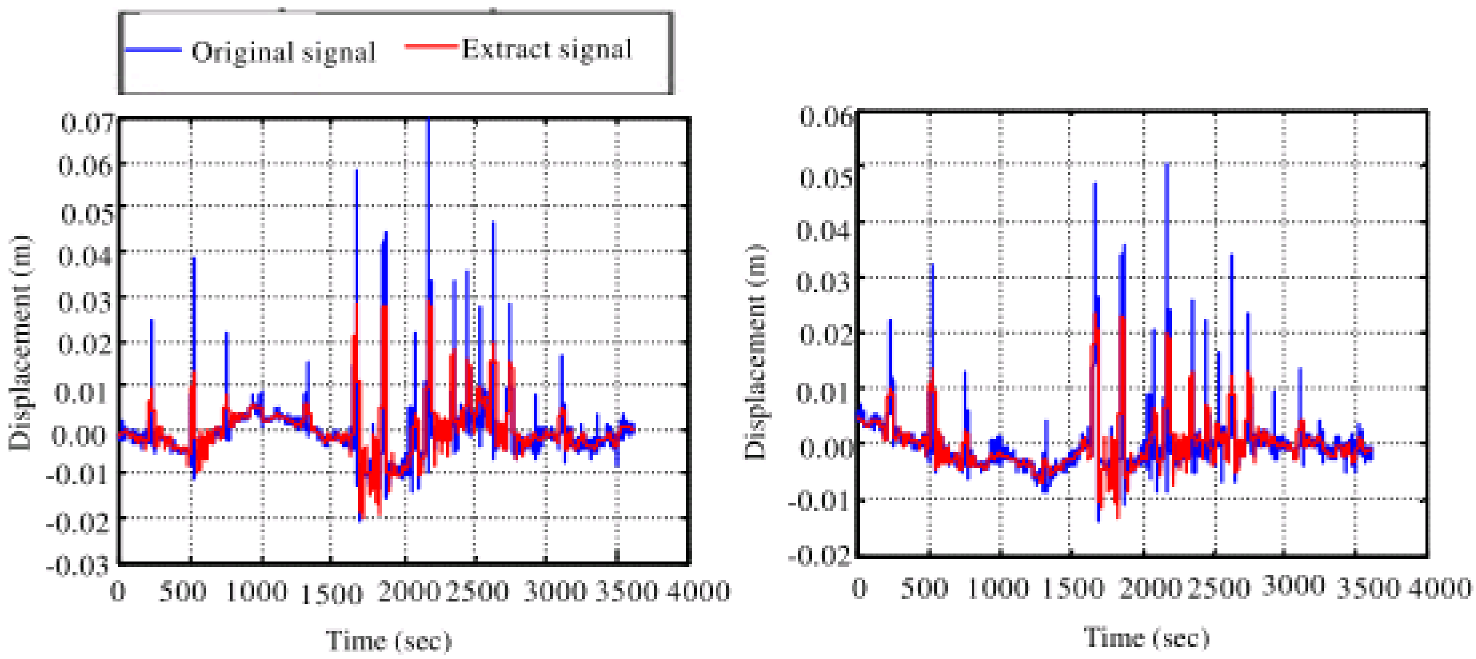

Fig. 3: Time history of movement of a southern tower bridge in (a) X and (b) Y-directions

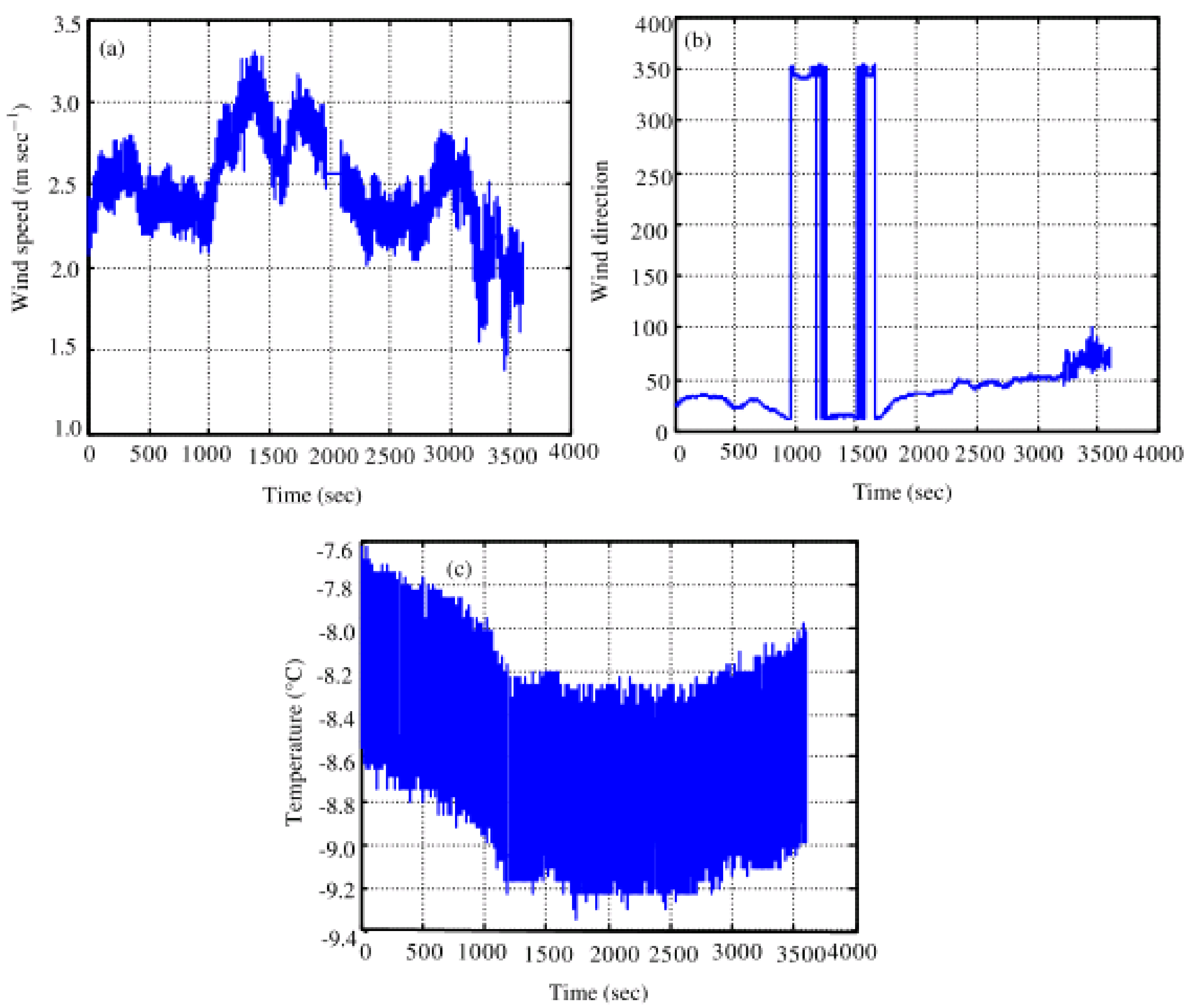

Fig. 4: Time history of wind and temperature for the bridge, (a) speed, (b) direction and (c) temperature

Transform (FFT) which is not different from Discrete Fourier Transform (DFT). It is an effective and excellent algorithm for the calculation of DFT. Yet, as DFT has periodic characters, it is assumed that the final sample of the signal is followed by an initial sample of the signal in the spectrum calculation. In this case, a spectral leakage occurs as a result of the signal energy leakage to other frequencies.

In order to minimize this effect, it is proposed to multiply the signal by window function as expressed in Eq. 1. This function characterizes with amplitude slowly approaches zero at the edges before the transformation is performed.

$$w(i+1) = 0.54 - 0.46\cos\left(2\pi\frac{i}{n-1}\right) \quad (1)$$

FFT is applied to Y (tip) = Y (ti)* w (i) windowed observations, X (n) FFT coefficients in Eq. 2 are obtained.

$$X(n) = \sum_{t_i=0}^{N-1} Y(t_{ip}) e^{-jn\frac{2\pi}{N}t_i} \tag{2}$$

For $0 \le n \le N - 1$, the calculation of X (n) in Eq. 2 requires N complex multiplications and N-1 complex sums. Computing all the N of the X (n) values demands N^2 complex multiplications and N^2-N complex additions. The FFT coefficients X (n) are in the complex plane but this representation does not aid interpretation. Therefore, the power of the FFT signal is:

$$P_{xx}(n) = |X(n)|^2 \tag{3}$$

where, P_{xx} (n) values are calculated with the use of Eq. 3 and dominant frequencies in the series are determined by the density frequencies of the signal. The nature frequency ranged from 0.01 to 0.50 N, where N is the number of story (Nayeri *et al*., 2008). In this case, the tower height of Yonghe bridge is 62.50 m. Approximately, it was assumed that, the height of story equal to 2.80 m and the tower frequency between 0.22 to 11 Hz. In addition, the frequency components of the bridge towers were calculated at high of 0.2 Hz. The first mode natural frequencies of the southern tower bridge were shown in Fig. 5a, b and 7a, b. It was found that the GPS and accelerometer values in the X-direction to be 0.32 and 0.41 Hz, respectively, whereas these values were found to be 0.31 and 1.1 Hz, respectively in Y-direction.

Acceleration measurements: Figure 6a and b show the values registered by the accelerometer at a 100 Hz-data rate on the same time of GPS observation. It is possible to note that the output is quite noisy. In spite of that, the accelerometer values obtained have a absolute range variation of 2.42 and 0.14 m sec^{-2} with average 0.01 and 0.00 m sec^{-2} in X and Y-directions, respectively.

The FFT was applied to a 2×10^{16} sample of accelerometer data and the frequency spectrum results are shown in Fig. 7a and b.

Torsional displacement: The tower displacements consist of horizontal displacement of X-axis and Y-axis as well as torsional displacement. For this reason it is assumed that the first coordinates observed denote GPS_1 coordinates as (X_1, Y_1) and next observations are GPS_i coordinates as (X_i, Y_i), so the torsion displacements T (t) are measured from the first coordinate observed. The T (t) and the coordinates values at time t can be computed as follows:

$$T(t) = \tan^{-1}\left(\frac{\Delta Y(t)}{\Delta X(t)}\right) = \tan^{-1}\left(\frac{Y_i(t) - Y_1(t)}{X_i(t) - X_1(t)}\right) \tag{4}$$

The computed T (t) values of the tower are shown in Fig. 8a. In general, a tower bridge is assumed a rigid diaphragm with infinite stiffness. Therefore, the distance between two GPS stations (i.e., GPS coordinates) may maintain zero m during the measurement periods. The distance error between two GPS stations during the measurement periods can be computed as follows:

$$\Delta S = \sqrt{(\Delta X)^2 + (\Delta Y)^2} \tag{5}$$

Using this distance error can indirectly evaluate the accuracy of the GPS displacement measurement system. The computed distance error between two GPS stations measurements as shown in Fig. 8b and was maintained with 8 cm range.

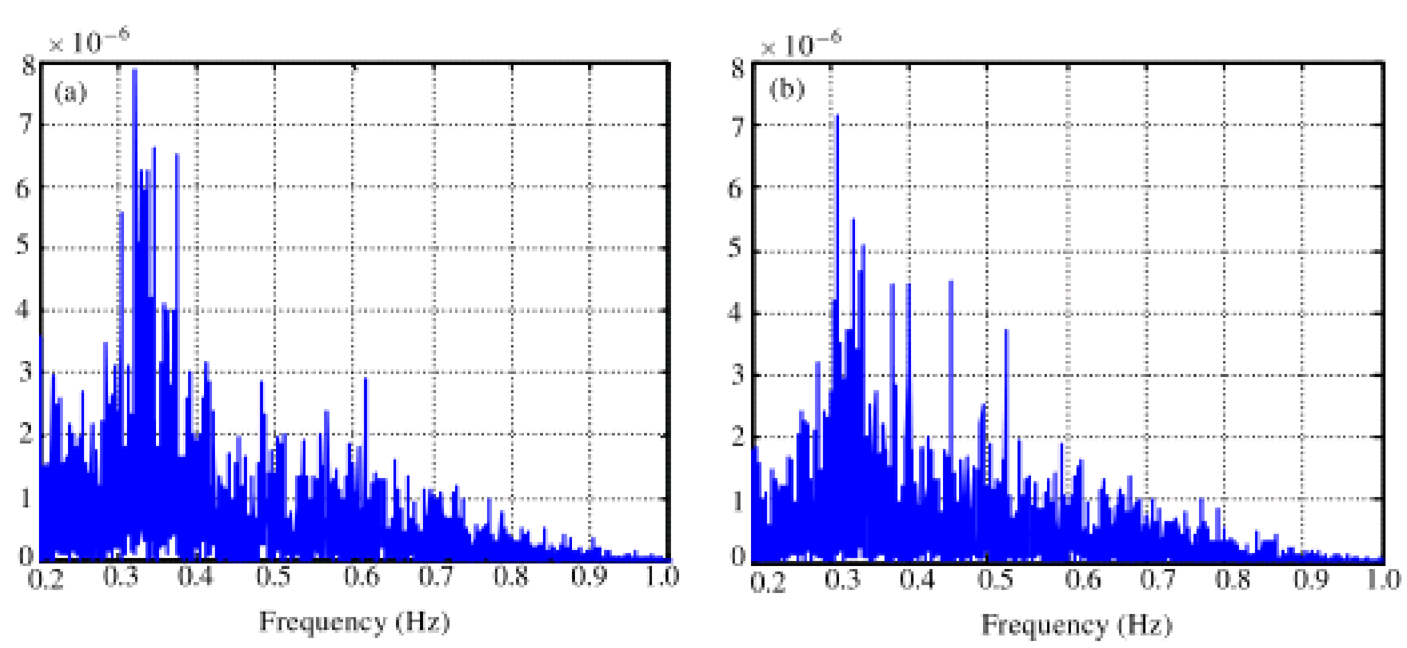

Fig. 5: Fundamental natural GPS signal frequency plot: (a) X-axis frequency and (b) Y-axis frequency

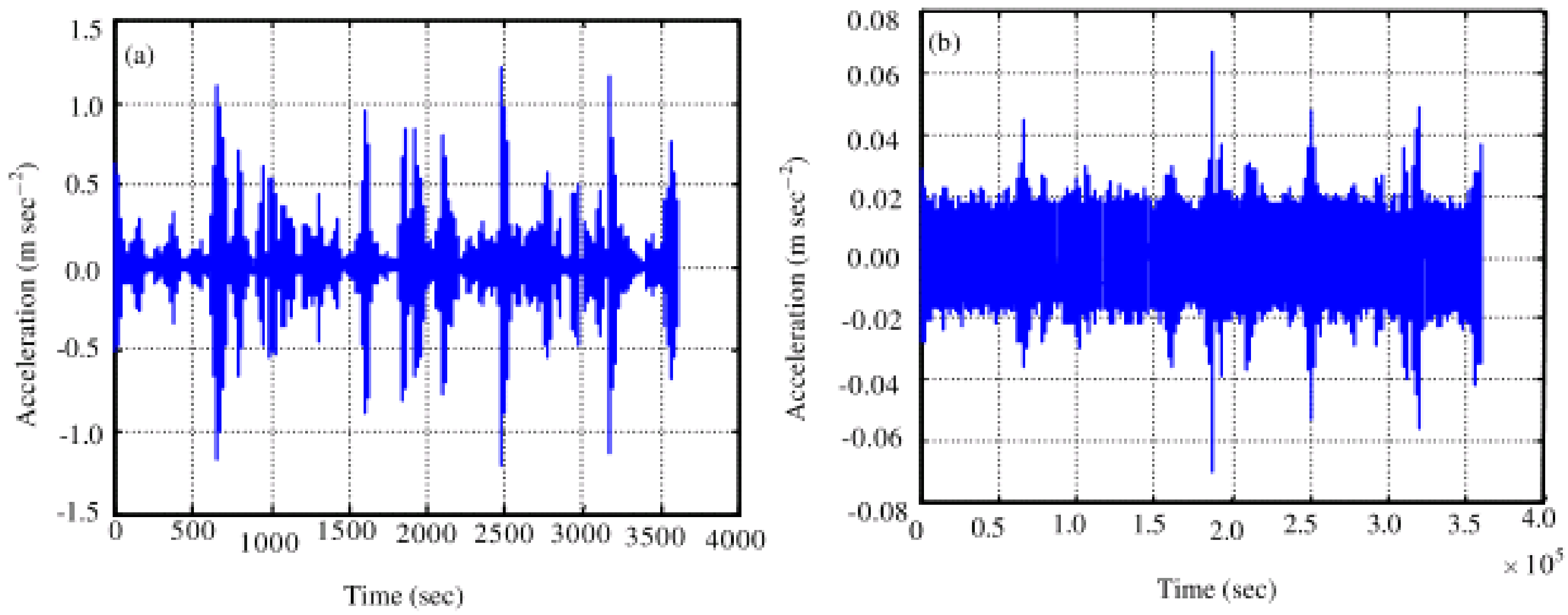

Fig. 6: Time history of accelerometer the southern tower bridge, (a) X and (b) Y-directions

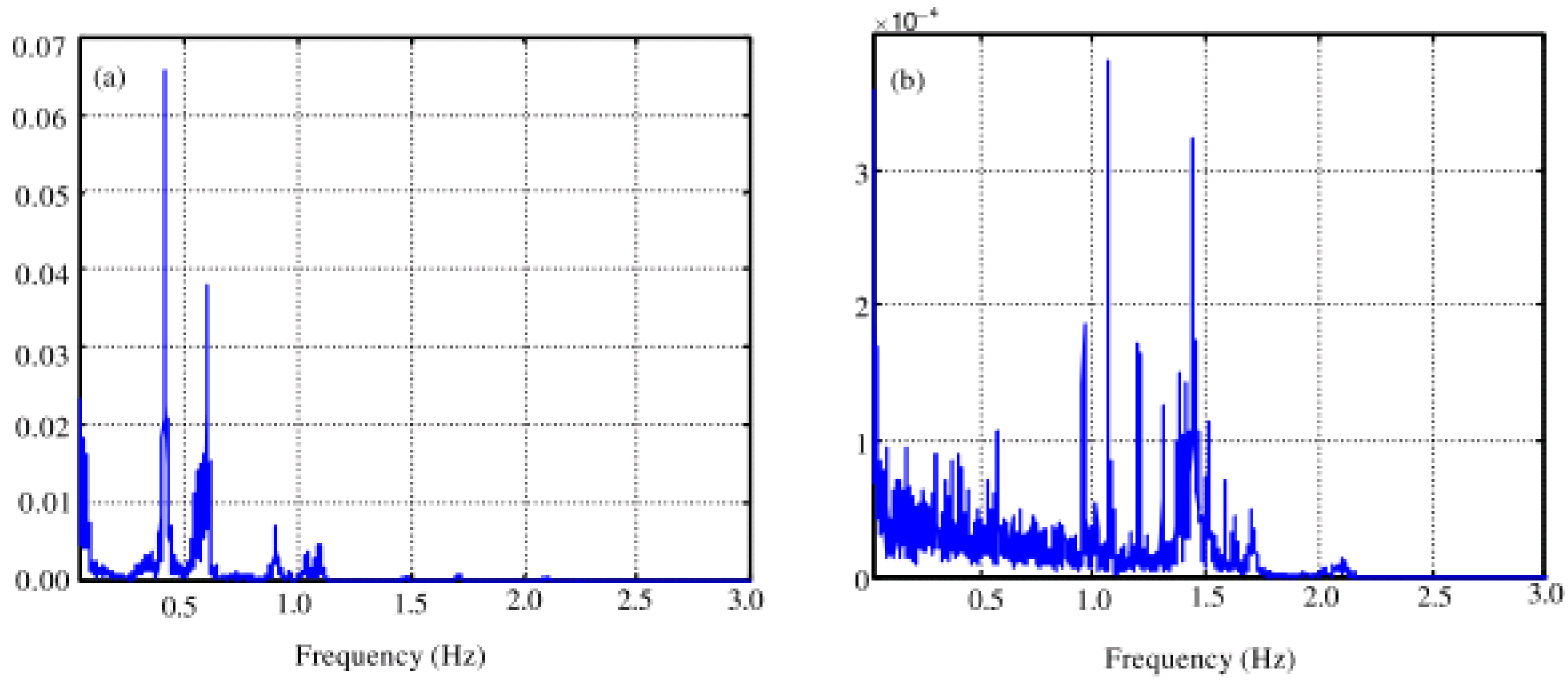

Fig. 7: Fundamental natural Accelerometer signal frequency plot, (a) X-axis frequency and (b) Y-axis frequency

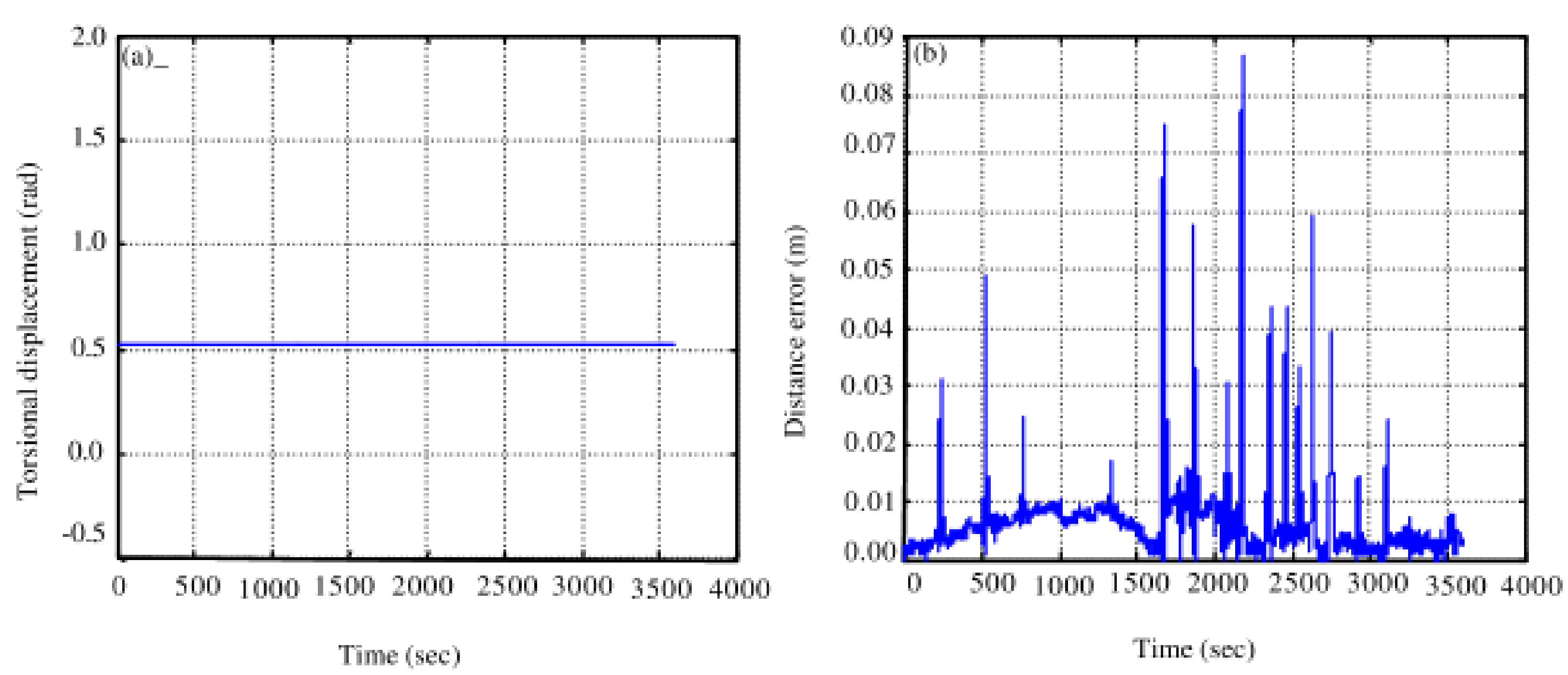

Fig. 8: (a) Torsion displacement and (b) the distance error between the first and series positions

DEFORMATION ANALYSIS

Deformation analysis is performed using the certain epoch's results. F-test statistical analysis is adopted to find out the deformation in the tower. In this study, the statistical analysis of the deformations obtained from wden Matlab function is based on the first observation group as shown in Fig. 9 (i.e., this group is considered as a datum group and consists of the first 3 sec observations). The time series of the next groups in X-direction are related to the first group and calculated as follows:

$$T_i = \frac{d_i^2}{\sigma_{d_i}^2} \tag{6}$$

$$d_i = X_i - X_c \tag{7}$$

$$\sigma_{d_i}^2 = \sigma_i + \sigma_c \tag{8}$$

Where:

- T_i = Test value for the X-direction deformation at the ith estimation interval
- d_i = The difference between the mean of the datum group (c) and the next time series groups
- σ_i = The variance in the X-direction each 3 sec estimation at the i^{th} estimation interval
- σ_c = The variance in the X-direction for the first 3 sec case estimation interval
- σ^2_{di} = The variance in the difference vector

For deformation analysis, the zero and alternative hypotheses are defined as follows:

$$H_0 : E(di) = 0 \qquad H_a : E(d_i) = 0 \tag{9}$$

If $T_i \geq F(1\text{-}\alpha, 2, df)$, F-test depended on the degree of freedom (df) at the 95% confidence level. It is considered that the difference vector (d_i) is significant and that there is indeed a deformation in the X-direction component (Schroedel, 2002). The same analysis procedure is also performed in the Y-direction components, as shown in Fig. 10a and b.

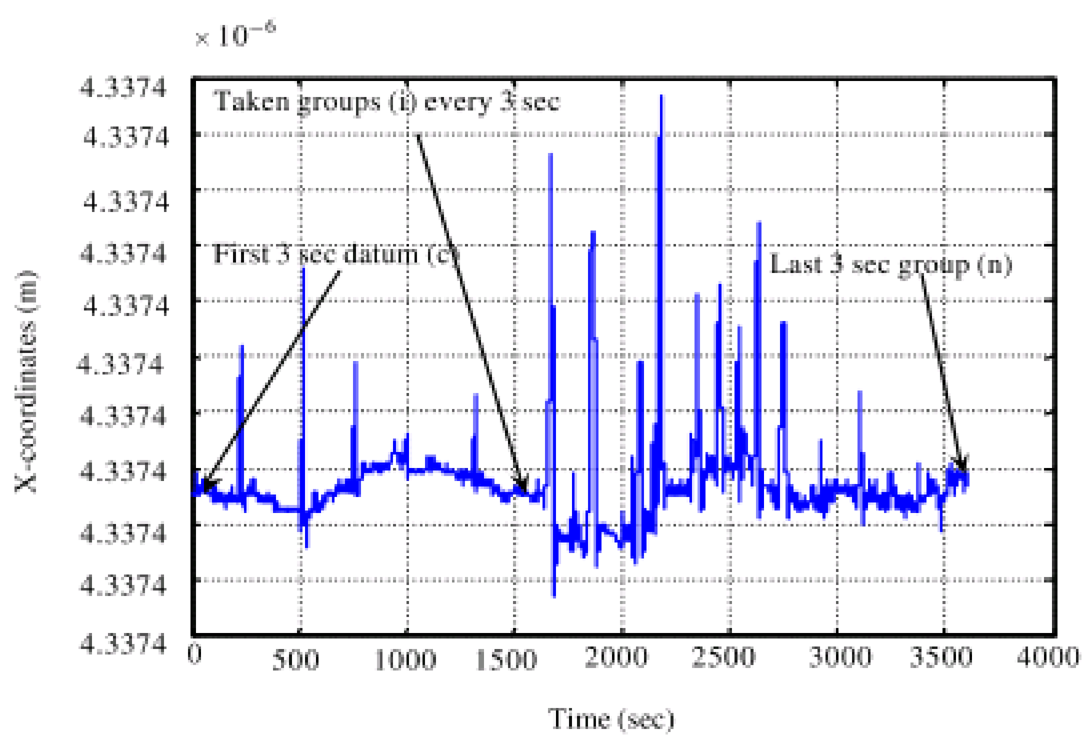

Fig. 9: Continuous deformation analysis scheme

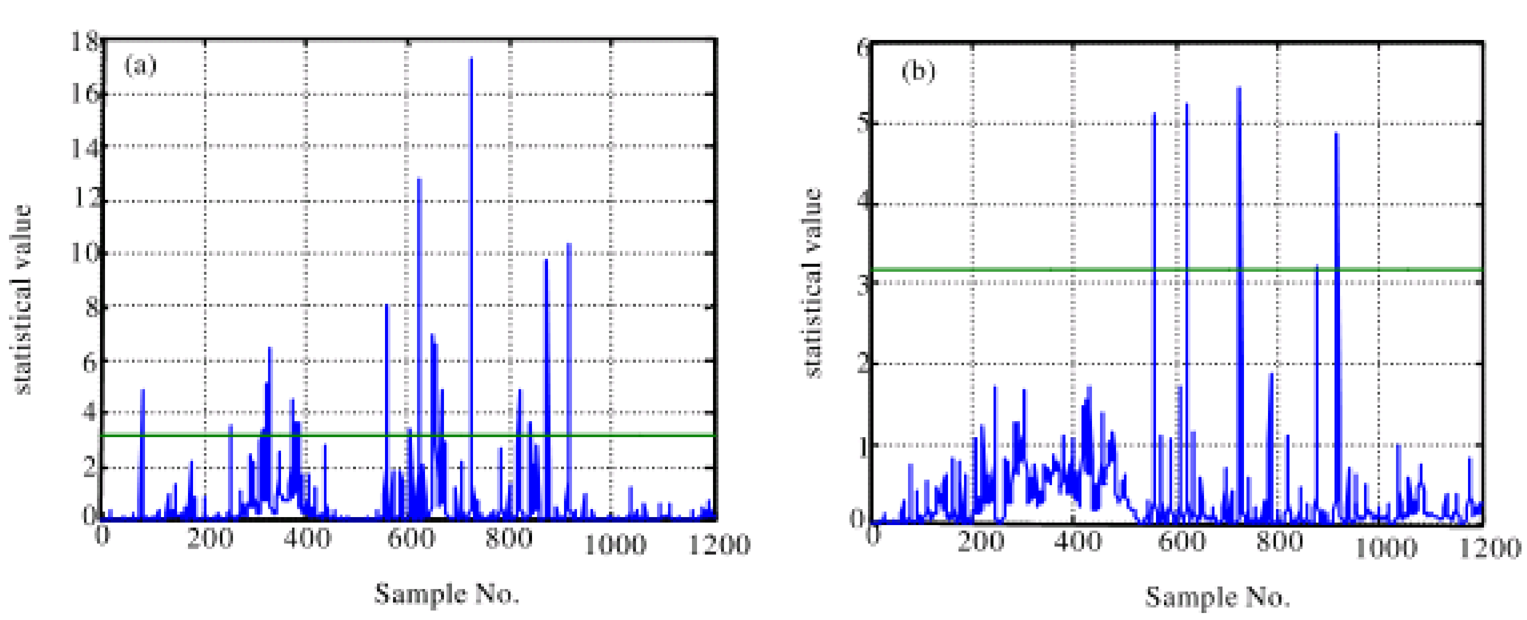

Fig. 10: Continuous deformation (blue) statistical tests (a) X-direction and (b) Y-direction

DISCUSSION

As shown in Fig. 3, the displacement in X-direction is found to be between -20.02 and 28.91 mm with average value of 1 mm, whereas it was found to be between -13.02 and 23.38 mm with average value of 0.80 mm in Y-direction. Figure 3 also, revealed that the average directional displacement can be construed as a static component of the displacement while its dynamic component can be verified to be approximately 1 mm. The average wind speed during the observation period of the tower displacement measurement using GPS was 2.50 m sec^{-1} with the prevalent wind direction of 25° (Fig. 4).

These results revealed that the loads and traffic velocities affect the towers movements and the tower was moved in the opposite direction of the wind since the wind speed is equal to 2.50 m sec^{-1} (normal speed). In addition, it can be seen that the temperature has lower effects on the deformation, since, the difference in temperature was found to be 1.75°C (Fig. 4c).

From Fig. 3, it was found that the residuals between the original and extracted signals are 5.97 cm. This indicated that the noise of GPS signals is high. As well as, it can be seen that the wden function processing caused an increased in the signals accuracy by 20%. Therefore, it's recommended to use wden function in the extraction of GPS signals.

The obtained data from wavelet analysis were used to plot the power spectral density in X and Y directions as shown Fig. 5 and 7. From these Fig. 5 and 7 it can be seen that the power in the X direction is greater than that in the Y direction. This indicates that the power spectral density is a good parameter to detect the tower movements and this observation complies with the resulted obtained by Erdogan and Gulal (2009).

From Fig. 6, it can be seen that the range and average of acceleration in X direction is too high, which indicates that the tower movements in X-direction are critical. In addition, it can be seen that there is a difference between the calculated frequency from GPS and that calculated from Accelerometer signals. This reveals that the GPS system can be used to measure the deformation. Due to its signals errors, GPS can not used to measure the high frequency of dynamic behavior of tower. Thus, accelerometer must be added to the monitoring systems for measuring the high frequency of the structures.

Figure 8 shows that the T (t) is equal to 0.51 radian and the distance errors in almost of the observation period didn't exceed 1cm, which indicates that the tower movements are affected by the traffic loads. In addition, Fig. 8 shows that the GPS signals contain a complex error, which affects the accuracy of the calculated deformation values.

From statistical analysis, it can be seen that the tower movements are very clear in time periods from 400 to 900 sec in X-direction and 1600 to 2600 sec in both directions (i.e., X and Y-directions). These indicated that the movements of tower are not susceptible by the environmental effects and the results cited in Li *et al.* (2009) insure this fact.

CONCLUSION

Based on this limited study, the analysis of the results leads to the following findings:

- GPS signals noise contains complex errors and the signals accuracy obtained from the wden function increased by 20%. So, it's recommended to use wden function in the extraction of GPS signals
- Due to the GPS signals errors, GPS can not used to measure the high frequency of dynamic behavior of tower. Thus, accelerometer must be added to the monitoring systems for measuring the high frequency of the structures
- The power spectral density is a good parameter to detect the tower movements
- Based on the statistical analysis, it was found that the traffic loads are the main factor affects the tower movement, in addition the environmental effects are not susceptible on it
- GPS can be used as a trustworthy tool for characterizing the dynamic behavior of the low frequency bridges. With the advance of sample rate frequency of GPS receivers, the dynamic behavior of the bridges in high frequency can be measured

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