Structural Engineering and Mechanics, Vol. 36, No. 2 (2010) 129-147
DOI: http://dx.doi.org/10.12989/sem.2010.36.2.129

Simple geometrical model to analyze the motion detection of bridges based-GPS technique: case study Yonghe Bridge

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(Received July 29, 2009, Accepted April 30, 2010)

Abstract. This study deals with the viability of using a designed geometrical model consists of plane, polar coordinates (PC) and span length in the determination of bridges deformation. The data of a Tianjin Yonghe bridge located in the southern part of China as collected by RTK-DGPS technique and Accelerometer were used in the analysis. Kalman filter and fast Fourier transformation (FFT) analyses were used to determine the frequency. The results indicate that the designed plane and PC geometrical model are easy to calculate the long-time structural deformation monitoring. In addition, the observed frequency using GPS with the rate of 20 Hz doesn't give correction natural frequency of the observation structures.

Keywords: bridge; monitoring; RTK-DGPS; accelerometer; deformation; geometry; tower.

1. Introduction

The importance of bridge health monitoring and management has been recognized by authorities of long-span bridges throughout the world in securing proper operation of their important lifetime infrastructures and in protecting the vast investments made in road and rail transportation network systems (Wong 2004). The monitoring system is focusing to determine the magnitude and the direction of motion of the detail points representing the object (Mokarrami *et al.* 2004). There are three major factors upon which the selection of a measuring method highly depends: magnitude of displacement, frequency of movements and accuracy instruments (Armenakis 1987). The deformations of structure are the most relevant parameter to be monitored. Moreover, buildings can be damaged by earthquakes, typhoons, strong winds, increase live load, or even terrorist attacks. Many damaged buildings (especially steel ones) cannot be simply inspected by eye because there may be no major visible damage to the surface of fire-protection material covering structural members; therefore, it is essential to have a monitoring system built into the major structure (Li *et al*. 2004).

In the monitoring process, there are two mainly methods namely; physical and geometrical. The categories of these methods are illustrated in (Armenakis 1987). Physical methods are used to

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measure-usually unidimensional-relative displacements using various linear mechanical instruments in contact with the object (Armenakis 1987). Geometric methods are capable of monitoring both relative and absolute movements with respect to a given reference datum. These methods range from photogrammetric approaches to conventional- and satellite geodesy techniques (Armenakis 1987).

Many monitoring stations have been installed on some bridges that are under construction or have been built in many countries. For example, the Automatic Data-Acquisition System, which was set up on Skarnsunder diagonal cable stayed bridge that spans 530 m in Norway, can monitor wind vibration, acceleration, gradient, strain, temperature and the displacement for the bridge automatically. Also, "the wind and the structure health monitor system" had been installed on Qingma Bridge that span 1377 m in Hong Kong for monitoring safe status of the entire bridge (Yu *et al*. 2006). Since 1980s, deformation monitoring with Differential Global Positioning System (DGPS) has been deployed successfully in many parts of the world, In other hand, the Global Positioning System (GPS) are measured directly the geodetic coordinates positions (El-Rabbany 2002), so providing an opportunity to monitor, in real-time, the dynamic characteristics of the structure to which the GPS antennas are attached (Li *et al*. 2004). Preliminary studies have proved the technical feasibility of using real time kinematics (RTK) GPS to monitor dynamic structural response due to winds, traffic, earthquakes and similar loading events (Ashkenazi *et al*. 1997, Ramin *et al*. 2009, Kaloop *et al*. 2009). Although RTK-GPS has its own limitations, GPS can only give us the overall deformation of the building and thus little will be revealed regarding the location of the actual deforming position (Li *et al*. 2004). The clear resonant wave envelope would make it possible to evaluate the building's damping ability using the GPS or Accelerometers displacement measurements (Chris *et al*. 2008). Using only frequency changes might not be sufficient to uniquely determine the damage location (Yong 2005, Reborts *et al*. 2004).

However, the objectives of this research are: (1) To examine the RTK-DGPS technique in deformation monitoring of the bridge tower; (2) To use the Kalman filter (KF) technique in GPS data processing; (3) To determine the bridge deformation using the geometrical analysis; (4) To detect the reasons affecting bridge damage; (5) To set a relation between the movement of towers and bridges damage; and (6) To estimate the damage time of bridge.

2. Bridge description and SHM system

The Tianjin Yonghe Bridge, as shown in Fig. 1, is one of the earliest cable-stayed type constructed in China_mainland. It comprises a main span of 260 m and two side spans of 25.15 + 99.85 m each. This bridge opened to traffic since December 1987. Its closure segment was damaged after 19-year operation and return to work in 2006 after repairing. As for the repair and rehabilitation, the girder over the mid-span was re-constructed; other segments were repaired and rehabilitated by mud jacking to the cracks of the girder. At the same time, all stay cables were replaced. For safety assurance, a sophisticated long-term structural health monitoring system has been designed and implemented by the Research Institute of Structural Health Monitoring and Control of Harbin Institute of Technology (HIT) to monitor the structural performance (as shown Fig. 2). The structural health monitoring system for the Yonghe Bridge comprises a data acquisition and processing system with a total of approximately 179 sensors, including accelerometers, GPS, strain gauges, displacement transducers, anemometers, temperature sensors and weight-in-motion sensors, permanently installed on the bridge.

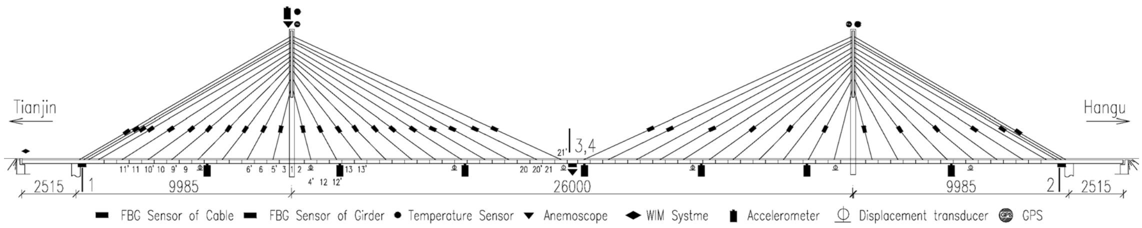


Fig. 1 The elevation diagram of Yonghe Bridge and positioning of rover GPS

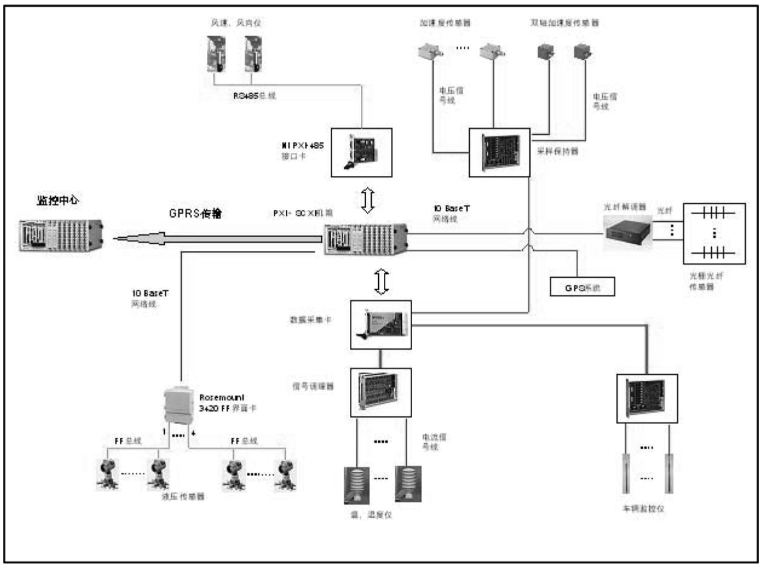


Fig. 2 The structural health monitoring system of Yonghe Bridge

3. Data collection

To study the viability of using state-of-the-art dual frequency code/carrier GPS receivers to monitor structural movements, trials three GPS receivers were set up: two on the top of the towers. Additionally, another receiver was set up as a reference station on stable ground in a position that no buildings have surrounded it, in order to reduce Multipath effect (Roberts *et al*. 2004, Raziq *et al*. 2006), as shown in Fig. 3 (2002 is north tower, 2001 is south tower and base is a reference station). The positioning of receivers related to WGS84. The GPS receivers used were LEICA GMX902 antenna (24 channel L1/L2 phase, SmartTrack technology, solid and small, water resistance (IP67) anti vibration, accuracy: 1 mm + 0.5 ppm (horz.); 2 mm + 1 ppm(ver.)) and pre-processed data using the software GPS Spider 2.1 and coordinate components for each observation epoch was derived. The GPS data rate was 20 Hz on each direction. Due to the large data files, the sessions were split into every one hour for processing purposes. The system of RTK-DGPS was used. The resulting coordinates transformed into the bridge coordinates was calculation. The local coordinates of the bridge are Y-direction with the flow traffic direction and X-direction is perpendicular on Y-direction.

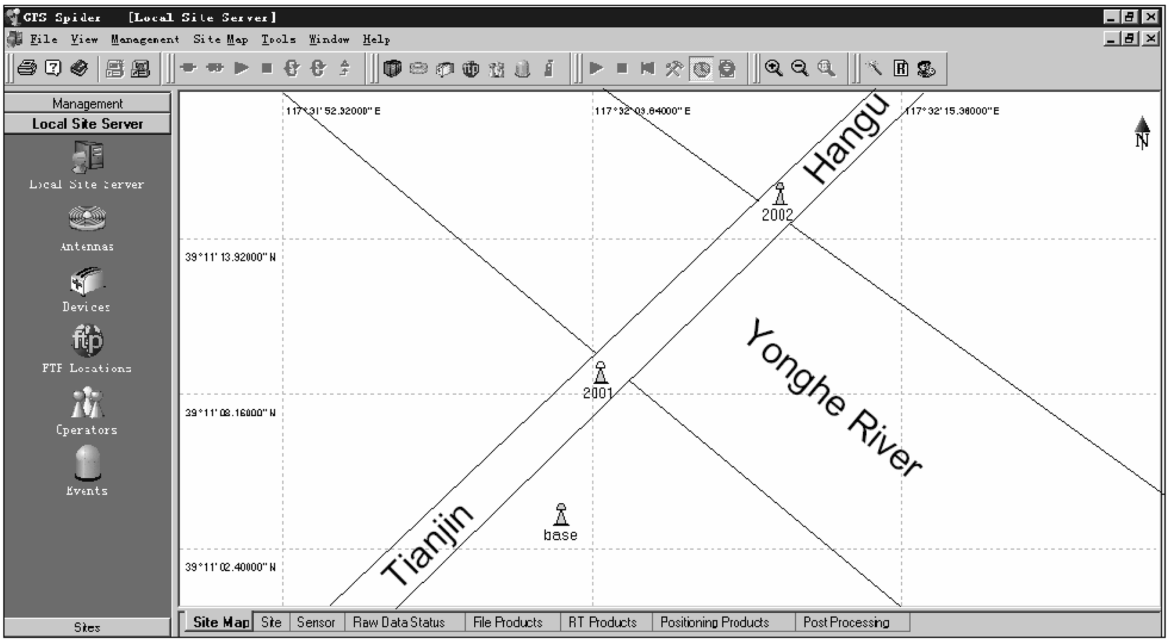


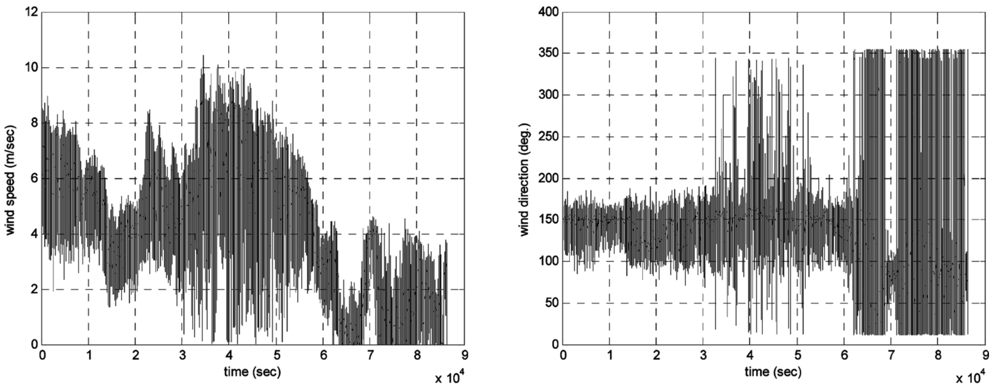
Fig. 3 The GPS dynamic monitoring scheme

(a) (b) (c)

Fig. 4 The shape of cracks at (a) abatement (at 48.2 m from the left bridge beginning), (b) mid span and (c) south tower (these photos are taken in August 2008)

The present study was focusing on the south tower movements whereas in August 2008 shows cracks near than the south tower as shown in Fig. 4.

From observed the available wind speed and direction was seen that the maximum wind speed (12 m/sec) is happened in January 2008. According to available weather observed, wind speed averaged 5 m/sec from August 2007 to January 2008 with its direction from 100 degree (SEE) to 330 degree (NNW). The wind direction was mostly at 160 degree cross to the tower side.



(a) (b)

Fig. 5 Sample of the environments observation in 01 January 2008 (a) wind speed, (b) wind direction

Table 1 Deflection in tower due to temperature

Coefficient of thermal expansion, α	12×10^{-6}/°C
Maximum temperature	28
Minimum temperature	- 6
Change in temperature, ΔT	34
Length of the tower, H	62.50 m
Deflection in tower, δ	0.0255 m

Fig. 5 was shown sample of the observed environment effects on the tower. These are the wind speed and wind direction respectively.

From the available temperature observed, the average minimum temperature in Tianjin Yonghe bridge location is −3°C in December and January whereas the average maximum temperature is 25°C in August. The minimum record temperature is −6°C in December and maximum record temperature is 28°C in August. So the simply calculation of temperature effects in the bridge tower is

$$\delta = \alpha \cdot \Delta T \cdot H \tag{1}$$

As the Table 1 shown, the deflections in the bridge towers due to temperature affects are not very large.

Also, from the available traffic observations, Table 2 shows sample of the vehicle loads and velocity.

Most the vehicles were paths from Tianjin to Hangu (channel 1) from October 2007 to July 2008. From the table, it can be seen that the velocity of traffic was increased from opening the bridge to January 2008. And the vehicle loads was increased in channel 1 to January 2008.

Table 2 The mean available vehicle loads and velocity

Date	Vehicle load (ton)	Vehicle velocity (m/sec^2)
08-2007	1.6338	47.89
10-2007	6.0302	51.9962
12-2007	4.4189	53.5024
01-2008	5.8676	58.3684
07-2008	4.2096	54.9486

4. Monitoring geometry models

For analyzing the signals, 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. The Kalman filter (KF) is accurately one of the methodologies to eliminate the noise of dynamic signals; The KF was designed to estimate the linear dynamic systems (Haykin 2001, Mohinder *et al*. 2007). According to (Grewal *et al*. 2001, Wang 2008), the KF is an estimator for what is called the linear-quadratic Gaussian, while (Moon *et al*. 2000) claims that the KF is simply an optimal recursive data processing algorithm. The mathematical form of the KF consists of two independent models, the dynamic and measurement models. The formula of KF shows in Appendix (A).

After cleaning of GPS signals, comparison between the cleaning signals to analyze the deformation. And it used the fast Fourier transformation (FFT) to analyze the spectrum features. MATLAB program was designed to calculate the KF and frequency of the GPS signals.

4.1 Plane monitoring model

The following derived equation of plane will be accurate position of the surface. The equation of plane in three dimensions can be written in the form

$$aX + bY + cZ + d = 0 \tag{2}$$

Where:

a, *b* and *c* are unknown parameters of accurate position of the surface.

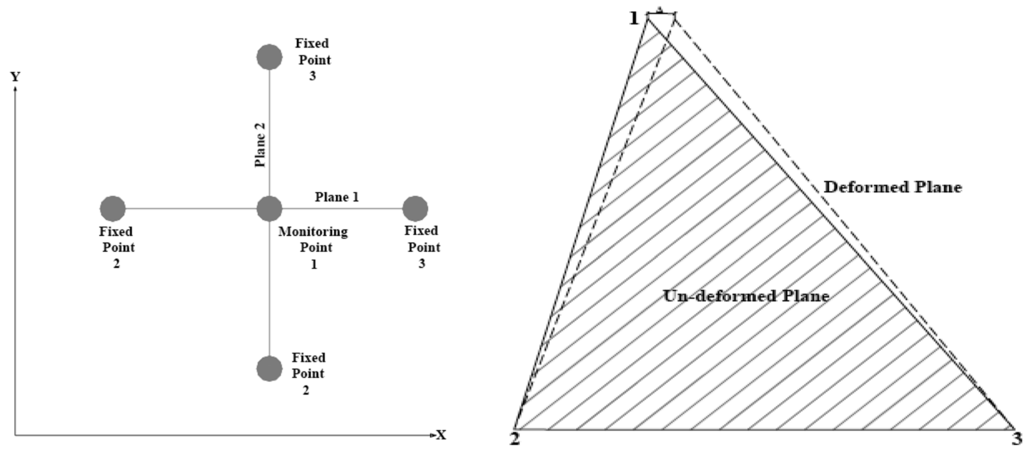
The unknown parameters can be calculated by following equation (Hearn *et al*. 1994)

$$\left.\begin{aligned} a &= Y1\ (Z2 - Z3) + Y2\ (Z3 - Z1) + Y3\ (Z1 - Z2) \\ b &= Z1\ (X2 - X3) + Z2(X3 - X1) + Z3(X1 - X2) \\ c &= X1\ (Y2 - Y3) + X2(Y3 - Y1) + X3(Y1 - Y2) \\ d &= -X1\ (Y2\ Z3 - Y3\ Z2) - X2(Y3\ Z1 - Y1\ Z3) - X3(Y1\ Z2 - Y2\ Z1) \end{aligned}\right\} \tag{3}$$

Where:

($X1$, $Y1$, $Z1$), ($X2$, $Y2$, $Z2$), ($X3$, $Y3$, $Z3$) are the coordinates of un-deformation plane of points 1, 2 and 3 as shown in Fig. 6.

The monitoring for the plane was calculated by the parameters of unloaded case and then calculation of the deformation loaded plane as the following equation



(a) (b)

Fig. 6 The geometry plane deformation monitoring (a) plan, (b) elevation

$$\Delta_i = \frac{|aX_i + bY_i + cZ_i + d|}{\sqrt{a^2 + b^2 + c^2}} \tag{4}$$

Where:

Δ_i is the deformation value of plane i relative to the un-deformed plane area. This value is perpendicular on the un-deformed plane as shown in Fig. 6(a, b, c, d) is the parameters for the un-deformed plane, and (X_i, Y_i, Z_i) is the monitoring coordinate of the movement point i.

The SD of the deformation plane was calculated by the error propagation as the following equation

$$\sigma_\Delta^2 = \left(\frac{\partial\Delta}{\partial a}\right)^2 \sigma_a^2 + \left(\frac{\partial\Delta}{\partial b}\right)^2 \sigma_b^2 + \left(\frac{\partial\Delta}{\partial c}\right)^2 \sigma_c^2 + \left(\frac{\partial\Delta}{\partial d}\right)^2 \sigma_d^2 + \left(\frac{\partial\Delta}{\partial X}\right)^2 \sigma_X^2 + \left(\frac{\partial\Delta}{\partial Y}\right)^2 \sigma_Y^2 + \left(\frac{\partial\Delta}{\partial Z}\right)^2 \sigma_Z^2 \tag{5}$$

To determine the deformation values of monitoring points in X-direction and Y-direction were used the plane 2 and plane 1 respectively as shown Fig. 6(a).

4.2 Polar coordinates monitoring model

The polar coordinates (PC) is a two-dimensional coordinate system in which each point on a plane is determined by an angle and a distance. This monitoring method is depended on the assumed that the origin of the earth is a fixed point to monitoring the rover station point. Fig. 7 shows the PC system for the study bridge and the local axis of it. The following formula has been used to calculation the PC from the Cartesian coordinates system

$$r_i = \sqrt{X_i^2 + Y_i^2} \qquad i = 1, 2, \ldots, n \tag{6}$$

$$S_i = \mathrm{Tan}^{-1}\left(\frac{Y_i}{X_i}\right) \qquad i = 1, 2, \ldots, n \tag{7}$$

Where, (r_i, S_i) is the PC of point i and (X_i, Y_i) is the Cartesian coordinates of point i.

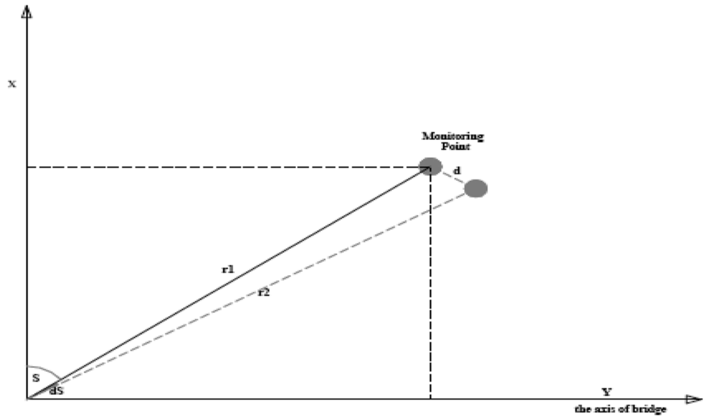


Fig. 7 The geometry polar coordinates system

From this Figure can be calculated the movement and direction of the movement for the monitoring point as following

$$\vec{d} = \vec{r}_2 - \vec{r}_1 \tag{8}$$

$$\angle dS = \angle S_1 - \angle S_2 \tag{9}$$

Where, r_1 and r_2 are the distance of PC, S_1 and S_2 are the angles of PC at time 1 and 2, d is the deformation of member and dS is the direction of deformation.

4.3 Span length monitoring model

The span length of bridge is affected by the load effects on the bridge. The distance between the two towers of bridge can be calculated from the GPS positioning on the studied bridge. Fig. 8 shows the effectiveness of traffic loads on top tower movement, as the same for other loads which affected the tower but may by take another shape.

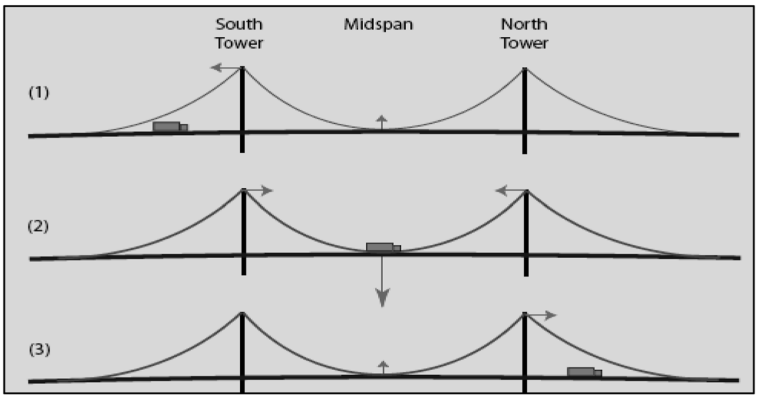


Fig. 8 The geometry traffic loads affects on the deck and towers movement

The distance between two observed points is calculated by the following equation

$$d(i) = \sqrt{(X_i - X_j)^2 + (Y_i - Y_j)^2}, \quad i = 1, 2, \ldots, n, \text{ and } j = 1, 2, \ldots, n \tag{10}$$

Where:
$d(i)$ is the span length between points i and j, and (X_i, Y_i), (X_j, Y_j) are the coordinates of tower points i and j respectively.

So if the safe span of bridge is observed can be monitoring the span length from the different between the span length at any time observed and the main safe span.

5. Structural analysis methodology

Structural analysis is required to determine whether significant movements are occurred between the monitoring campaigns. Geometric modeling is used to analyze spatial displacements. General movement trends are described using a sufficient number of discrete point displacements d_n (Δx, Δy, Δz) for n = point number. Comparison of the magnitude of the calculated displacement and its associated accuracy indicates whether the reported movement is more likely due to observations error (Schroedel 2002).

$$|d_n| < (e_n) \tag{11}$$

Where, d_n is the magnitude of the displacement and e_n is the maximum dimension of combined 95% confidence ellipse for point (n), It can be calculated as (Schroedel 2002)

$$e_n = 1.96\sqrt{\sigma_f^2 + \sigma_i^2} \tag{12}$$

Where, σ_f is the standard error in position for the (final) or most recent survey, σ_i is the standard error in position for the (initial) or reference survey. So, if $d_n < (e_n)$ the point isn't moved, else the point is moved (Schroedel 2002).

6. Results and discussion

Data were collected between June 2007 and June 2008 every months based on the local time from 11:00 AM to 2:00 PM. The analysis in this study 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.

Fig. 9 shows one sample of GPS signals and the KF results in X and Y-directions, respectively.

From the KF obtained results sited in Fig. 10, it can be seen that the different between the SD for GPS and KF coordinates is very clear. This indicates that the random noise of GPS signals is too high. The results also revealed that the percentage increase in residuals on May and June 2008 for X and Y coordinates are 90%, 50% and 173%, 100% respectively. This is related to the effects of deck cracks. Also, it can be seen that the SD values for KF are less than those obtained by GPS (i.e., the KF decreased the noise of signals by 28%). This indicates that the KF is accurately one of

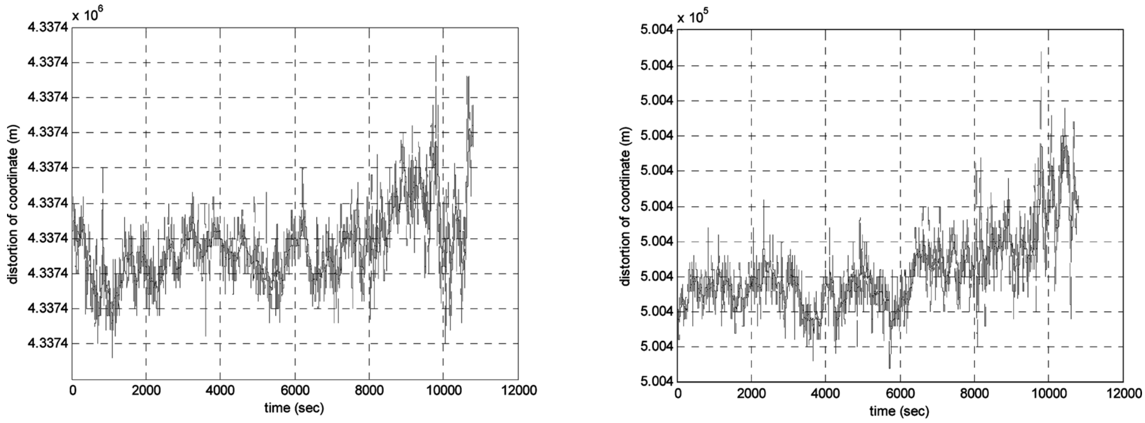


Fig. 9 A subset of the GPS results for the south tower site with the model kalman filter, in blue, superimposed (6 June 2007)

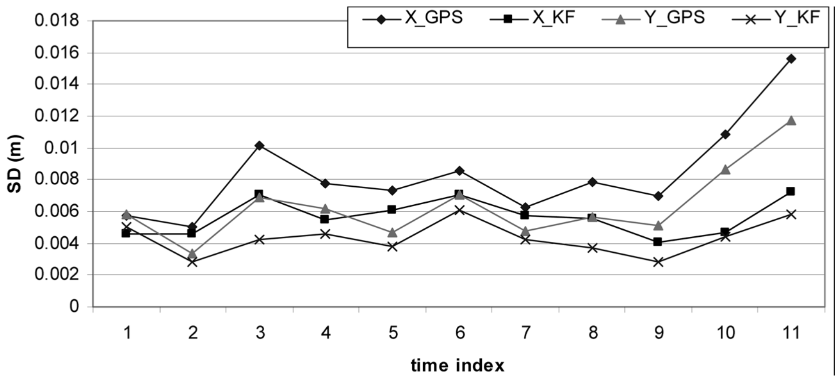


Fig. 10 The SD of KF and GPS signals for the X and Y coordinates

the methodologies to eliminate the noise of dynamic signals.

The south and north towers mean filters Cartesian coordinates, the long-monitoring time selection and time index are shown in Figs. 11 and 12, respectively. From these Figures, it can be seen that the maximum deformation of the south tower measured on February 2008 and of the north tower measured on December 2007 are 10.50 cm and 3.80 cm, respectively. These indicate that the load have much effects on the bridge that opened on August 2007. In addition, it is found that the movements of these towers happened on December 2007 to March 2008 are non-linear, which indicates the instability of the bridge. Fig. 11, also indicates that the maximum deformation of the coordinates pronounced on January and February 2008 and the upper point of the south tower is returned to its original position after 10 months. This can be attributed to the tower elasticity that absorbed the applied loads. Hence, it should be mentioned that the bridge GPS collection data under unload state on 6 June, 2007 are considered as a reference for the other monitoring date.

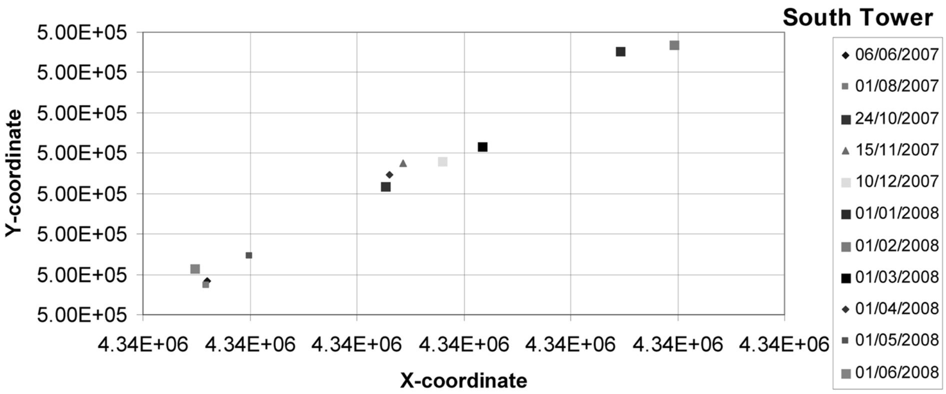


Fig. 11 The mean values of filters values for the south tower coordinates with the time monitoring

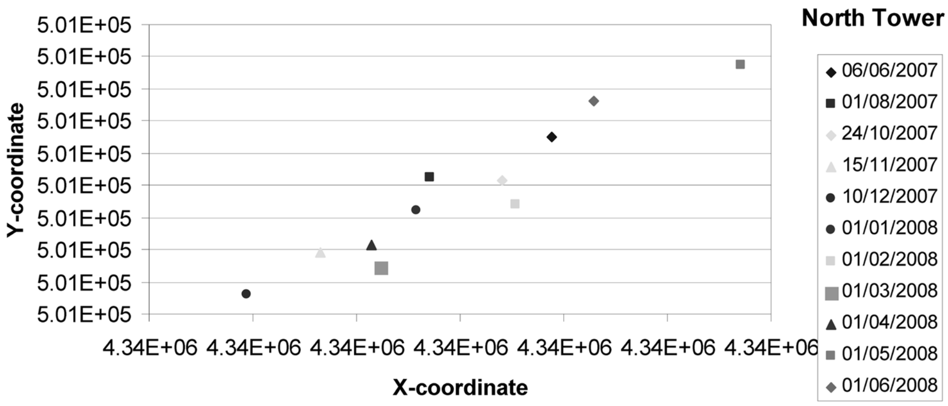


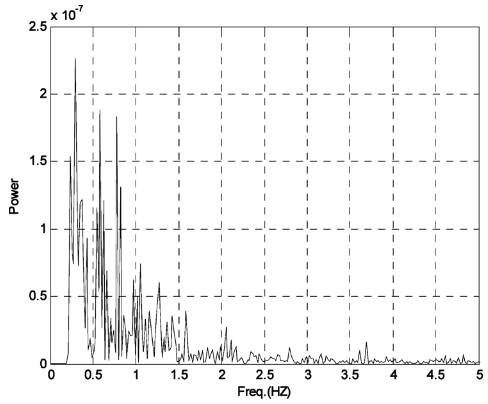
Fig. 12 The mean values of filters values for the north tower coordinates with the time monitoring

6.1 Power spectrum analysis

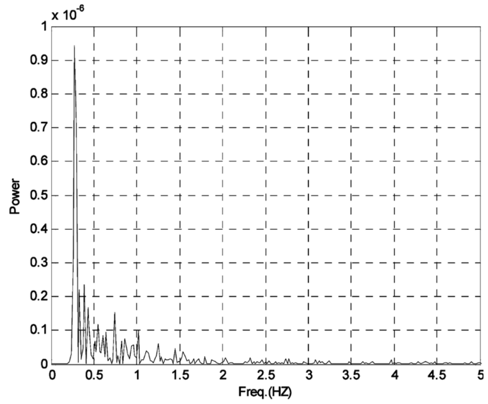
In order to split the static and dynamic motions and suppress the multipath effect, a low-pass filter has been designed based on the Fast Fourier Transformation (FFT) analysis to extract the very low frequency component from the GPS time series. The quasi-static motion is extracted by a band-pass filter (Chris *et al*. 2008). Then a high-pass filter is used to focus on the tower's natural frequencies range in order to obtain accurate resonant motion (Chris *et al*. 2008). Generally for the cable-stayed bridges and other large-scale buildings, their inherent structure vibration has a lower frequency of 0.1~10 Hz due to their huge mass (Yu *et al*. 2006). The nature frequency is equal approximately (0.01-0.50) N, where N is the number of story (Xiaojun 2008). For the tower of Tianjin Yonghe bridge the height of tower is 62.50 m. Assuming the height of story 2.80 m, so the frequency of tower is in between (0.22 to 11) Hz approximately.

Fig. 13 shows the different in GPS signals frequency calculated at X & Y-directions of the south tower on June 2007.

From this Figure, it can be seen that the frequency in Y-direction more clearly than in the X-direction due to the higher movement of the tower in the X-direction. Table 3 shows the first 5



(a)



(b)

Fig. 13 The frequency of the bridge towers (a) South tower X-direction, (b) south tower Y-direction (June 2007)

Table 3 The first 5 peaks frequency of GPS signals in X & Y-direction (Hz)

	X-direction					*Y*-direction				
Time index	f1	f2	f3	f4	f5	f1	f2	f3	f4	f5
06/06/2007	0.293	0.586	0.781	1.055	1.27	0.273	0.391	0.547	0.742	1.016
01/08/2007	0.371	0.488	0.625	0.859	1.133	0.312	0.644	0.762	0.898	1.152
24/10/2007	0.254	0.391	0.508	0.625	0.84	0.312	0.605	0.722	0.898	1.055
15/11/2007	0.352	0.508	0.957	1.074	1.191	0.41	0.508	0.918	1	1.094
10/12/2007	0.273	0.49	0.723	0.937	1.016	0.293	0.625	0.703	0.8	1.152
01/01/2008	0.273	0.449	0.664	0.9	1.211	0.273	0.508	0.723	0.9	1.074
01/02/2008	0.273	0.41	0.664	0.84	1.055	0.254	0.371	0.645	0.8	1.074
01/03/2008	0.371	0.45	0.703	0.82	1.211	0.312	0.45	0.55	0.94	1.094
01/04/2008	0.312	0.527	0.8	1.094	1.152	0.312	0.683	1.074	1.27	1.719
01/05/2008	0.312	0.371	0.468	0.8	1.368	0.312	0.371	0.527	0.684	1.27
01/06/2008	0.312	0.507	0.664	1.074	1.309	0.332	0.507	0.742	0.957	1.055

frequency of GPS signals and the time selection monitoring in the X and Y-directions.

Examining Table 3, it can be seen that the dynamic resonant peaks in X & Y-directions for the south tower are 0.293 Hz and 0.273 Hz, respectively, whereas the maximum ratios of frequency relative to the first date monitoring are found to be 26.6% and 50.2%, respectively. In addition, it is found that the first peak values on the last three months in X and Y-directions are equal, which indicates that the correlation between the movements is too high. The results in Table 3 and Fig. 14 revealed that of the fifth peak values calculated using GPS and the Accelerometer are much close, which indicates that the GPS frequency signals with 20 Hz doesn't given the accurately natural frequency, but it can be used for structural movement's monitoring as follow.

Fig. 15 shows the comparison between the first peak power spectrum in X and Y-directions for the south and north towers.

From this Figure, it can be seen that the different in mean frequency range and SD values for

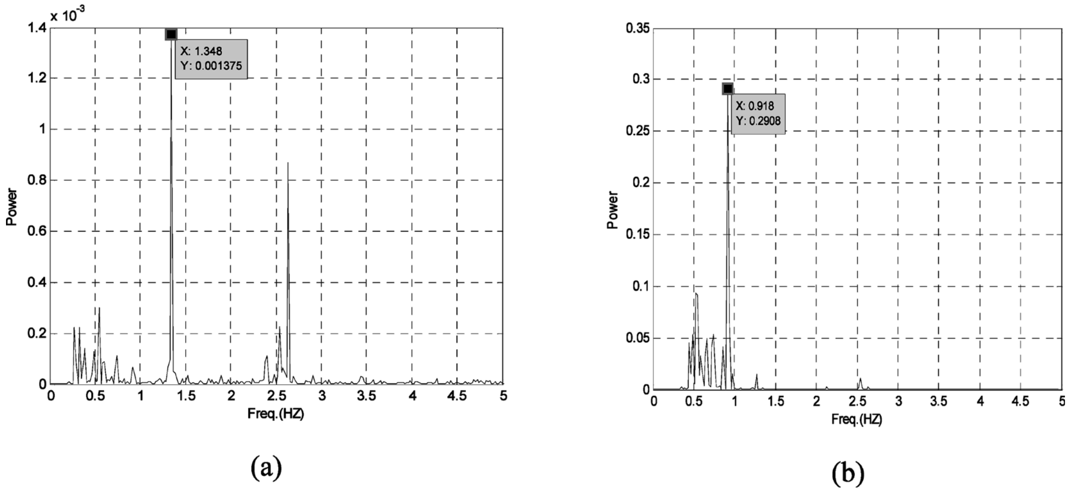


Fig. 14 The frequency of the bridge towers (a) South tower X-direction, (b) south tower Y-direction (from accelerometer data)

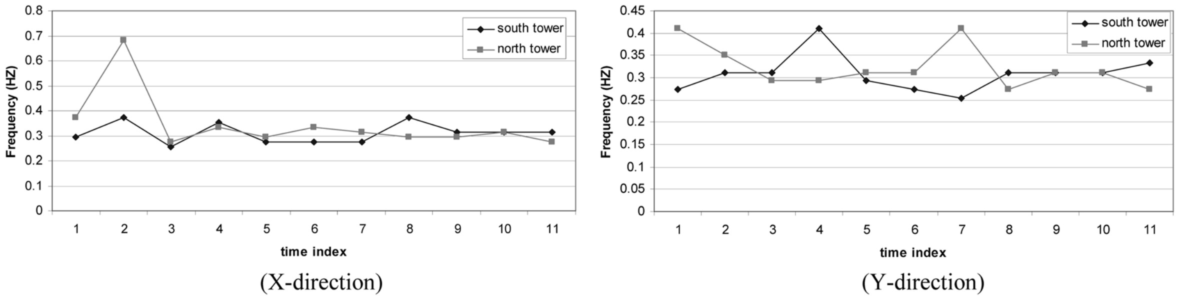


Fig. 15 The first peak power spectrum in two directions at two towers

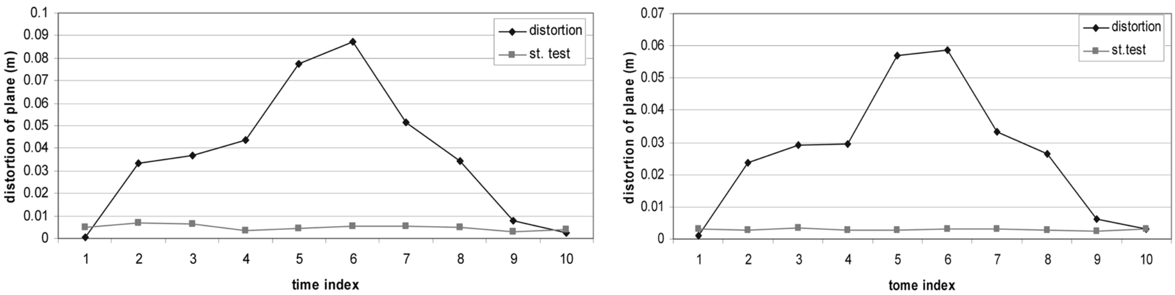
these towers in X & Y-direction are 0.062 ± 0.087 Hz and 0.057 ± 0.055 Hz, respectively. In addition, it can be found that the frequency values in X-direction for these towers are much close than those obtained in Y-direction, which indicates a non-linearity movement in Y-direction. The Figure, also revealed that the maximum different of the frequency in Y-direction on February 2008 and in X-direction on August 2007 are 0.156 Hz and 0.313 Hz, respectively. This indicates that the bridge deformation may be occurred around February 2008 due to the traffic loads effect that caused the towers movement.

6.2 Plane analysis

In order to determined the south tower deformation, a two fixed points (2 and 3) and one movement point (1) are assumed to create the geometrical plane shown in Fig. 6. In this Fig., the planes 2 and 1 are used in the deformation monitoring in X & Y-directions, respectively. The deformation in Y-direction is determined based on the assumptions that the fixed points coordinates in X-direction are equal to any values and in Y-direction to be the same value of unloaded tower for the same direction, and via versa is assumed for determined the deformation in X-direction. For the

Table 4 The parameters of two assumed planes at south tower

	Parameters	*a*	*b*	*c*	*d*
X direction	South tower	5050.000	0	0	-2.19E+10
Y direction	South tower	0	100.000	0	-5.00E+07



(a) (b)

Fig. 16 The distortion of plane in (a) X-direction and (b) Y-direction respectively for the south tower

Z-direction, the coordinates of the fixed points are assumed to be any equal values and the upper point of the tower is assumed to be the tower height.

Table 4 points out the obtained parameters from Eq. (3) and generally shows that the assumed coordinate's values have an effect on the parameters never on the deformation values.

From Table 4, it is found that the values of *c* parameter equal to zero for X and Y-directions due to the free errors in Z-direction. The values of *b* parameter are found to be zero in X-direction and for *a* parameter equal to zero in Y-direction, which indicates that the monitoring direction has an effect on the parameters values. For this model the mean Cartesian coordinate filtered from KF is used and as shown in Fig. 9. Fig. 16 shows the calculated deformation values in X and Y-directions using Eq. (4). From this Figure, it can be seen that the deformation of the upper tower point is very clear. Also, it can be seen that the maximum deformation in X and Y-directions are 0.087 m and 0.058 m, respectively. The statistical analysis of deformation in X and Y-directions at 5% level of significant indicates that the tower deformation was happened between August 2007 and June 2008. From this analysis, it can be concluded that the designed geometrical plane model can be used to determine the structural deformation.

6.3 PC analysis

In this analysis the unload cases data that collected on 6 June 2007 is predicted (smooth line) and used as a reference for other mentoring date. Fig. 17 shows the distance and angle of PC analysis for both prediction and signal.

From this figure and the calculation error signals using Eqs. (8) and (9), it can be seen that the deformation between the reference case and the other cases are significant, which indicates that the applied loads have more effect on the bridge since August 2008. Figs. 18 and 19 show the maximum, minimum and mean values of PC parameters (i.e., distortions of distance and angle). From these figures, it is found that the movement and angle of the tower to be 8.7 cm and, -1.015*10-08 radian respectively on February 2008, which indicate that the tower is moved towards

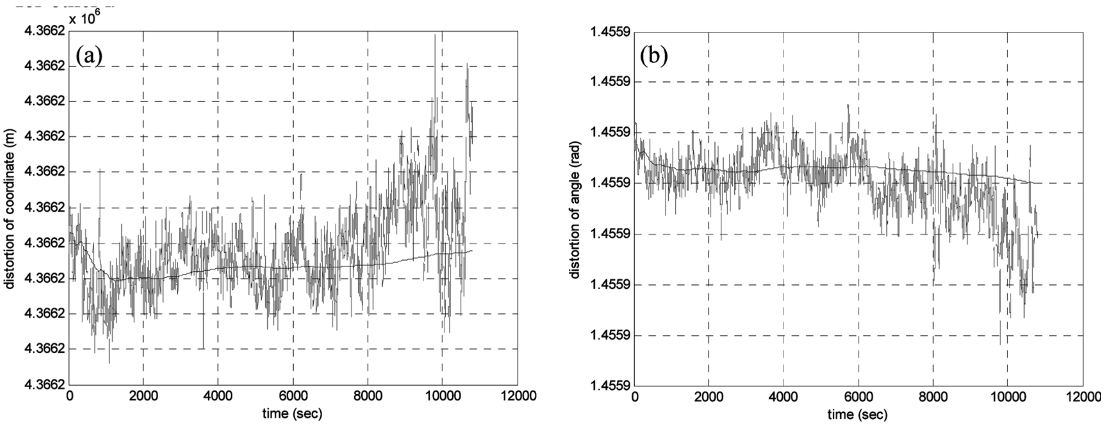


Fig. 17 The main signal (red) and prediction signal (blue) (a) distance PC and (b) angle PC

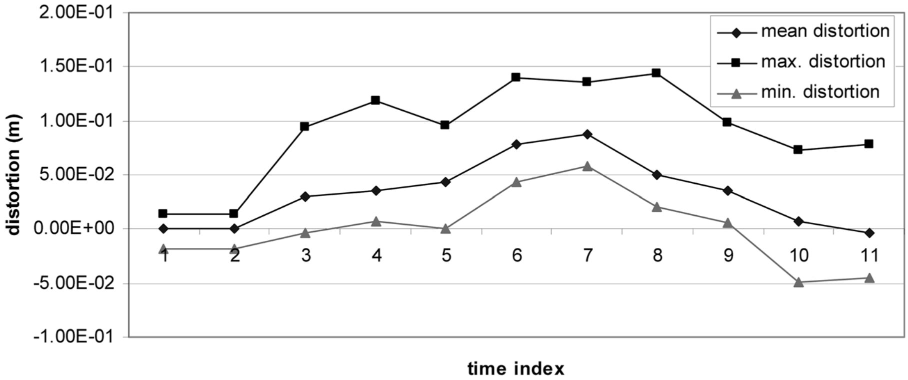


Fig. 18 The Maximum, minimum and mean for the distance PC distortion

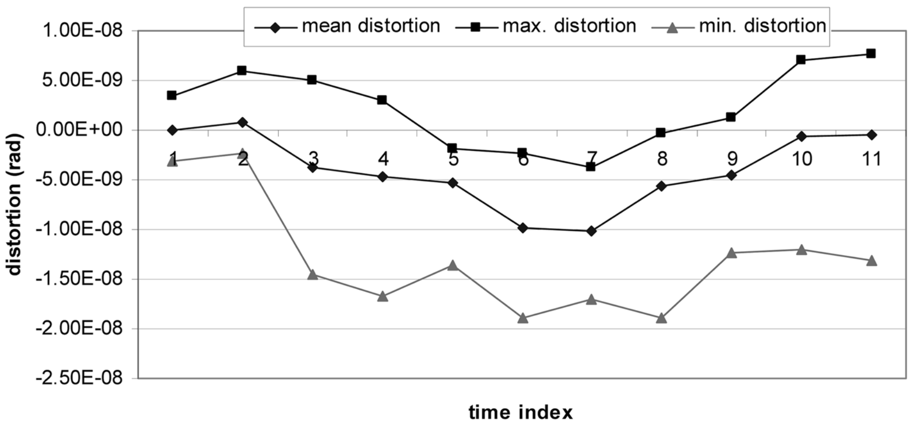
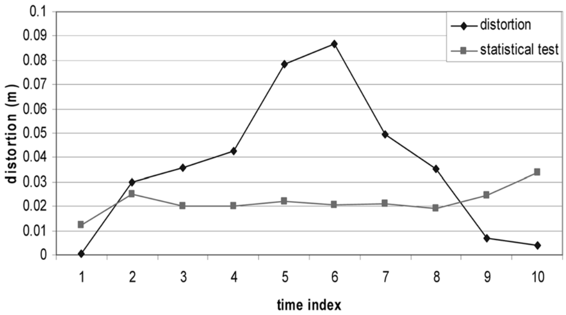
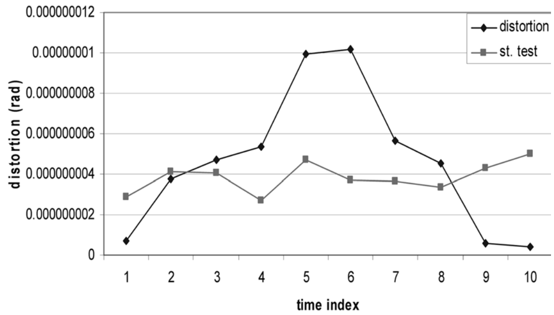


Fig. 19 The Maximum, minimum and mean for the angle PC distortion

NE direction due to the traffic load effects at the mid span. Fig. 20 shows the statistical analysis of the tower movement. From this figure, it is found that the maximum deformation in the distance and angle that happened between December 2007 and March 2008. Also, Fig. 20 indicates that deformation in the distance is happened between August 2007 and May 2008 and the SD of signals on May and June 2008 is greater than the other date due to the cracks. This means that the cracks are happened on April 2008.

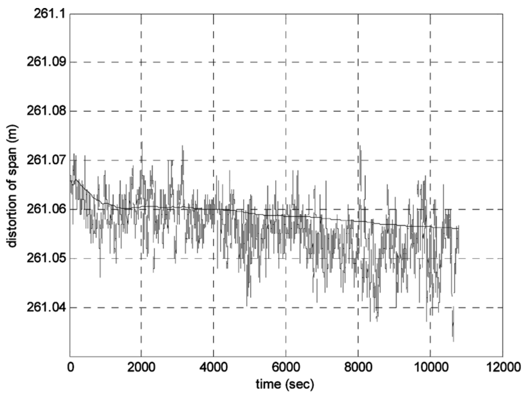


(a)

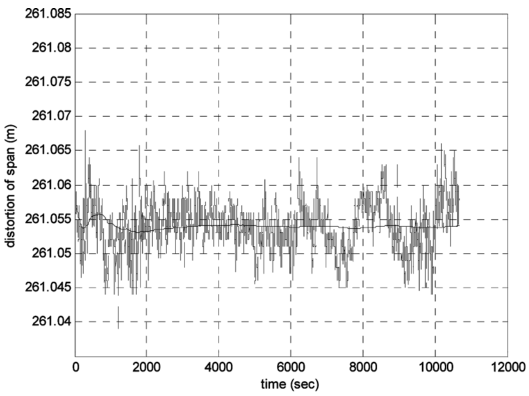


(b)

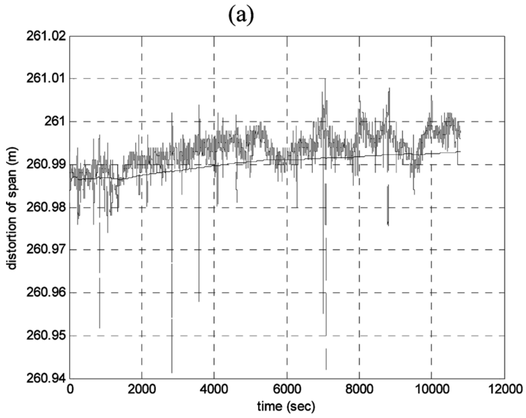
Fig. 20 The statistical test of the (a) distance and (b) angle for PC



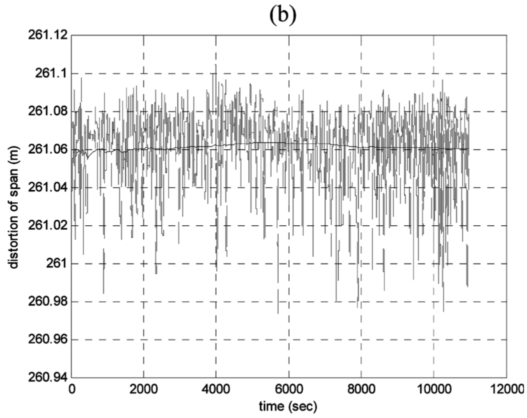
(a)



(b)



(c)



(d)

Fig. 21 A subset of the span length calculated with the model kalman predictions, in blue, (a) June 2007, (b) August 2007, (c) February 2008 and (d) June 2008

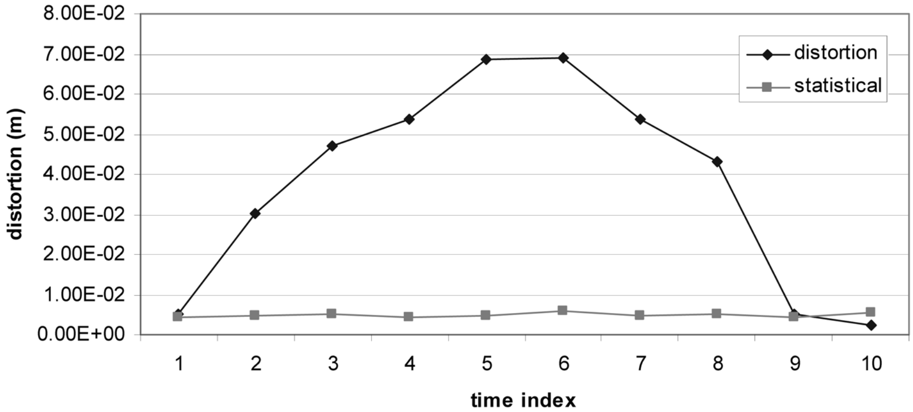


Fig. 22 Statistical test of the span length distortion

6.4 Span length analysis

This analysis is calculated using Eq. (10) to mentor the bridge span length as shown in Fig. 21. From this figure, it is found that the span length has significantly changed with the monitoring time. The mean of the span length predicted is decreased by 0.023% in between June 2007 and February 2008. This indicates that the towers are moved to towards the bridge between this period and its return to the original position after the cracks happened.

Fig. 22 shows the mean distortion of the span length predicted with it's statistically analysis. From this figure, it can be seen that after six months of bridge opening the deformation in span length is 6.9 cm due to the increased in traffic loads at mid span. From statistical analysis, it is found that the deformation is happened from August 2007 to May 2008. These results are close to that obtained in Fig. 16 and at the same time reflect that the cracks happened in the bridge deck caused by south tower deformation. Hence, it should be mentioned that this method can be applied if the direction of the movement for two towers are known.

7. Conclusions

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

1. The proposed surveying techniques using DGPS and RTK with long-time monitoring can provide valuable deformation data of the structural members.
2. The SD obtained from KF processing analyses of GPS data was increased significantly.
3. The observed frequency of GPS with the rate of 20 Hz doesn't give correction natural frequency of the observation body.
4. After six months of bridge opening, the maximum deformation was pronounced at 48.2 m far from the first left abutment.
5. It was found that the non-linearity between the movement and frequency for two towers is very clear in-between December 2007 to March 2008.
6. It was observed that the S-tower was returned to its original case after ten months of traffic opening.

7. The photographs in Fig. 4 demonstrate that the crack width on the second left abutment is greater than that on the mid span.
8. The designed plane and PC geometrical analysis models are easy to calculate the long-time structural deformation monitoring.
9. The tower movement towards inside developed a shear force that caused the cracks deck.
10. Based on the analysis models, environmental effects and traffic loads observation. It was found that the bridge deformation happened due to the traffic loads effect.
11. The traffic loads, non-linearity movement of the bridge and south tower movement are the main factors affect on the bridge life.
12. Based on the statistical analysis herein. It is recommended to use the plane model in the structural monitoring.

Acknowledgements

This research is financially supported by NSFC (Grant Nos. 50525823 and 50538020) and MOST (Grant Nos. 2006BAJ02B05, 2007AA04Z435 and 2006BAJ13B03). The first author is supported by Egyptian Ministry of Higher Education.

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Appendix (A)

1. The used Kalman filter formulas

$$x_k = F_{k,\,k-1}\, x_{k-1} + e_k$$
$$y_k = H_k\, x_k + V_k$$

Where;
x_k is the state vector at time t_k
x_{k-1} is the state vector at time t_{k-1}
$F_{k,k-1}$ is the transition matrix from time t_{k-1} to t_k
e_k is the noise vector representing the dynamic model at time t_k
y_k is the observation vector at time t_k
H_k is the design matrix for the measurement model
V_k, is the noise vector, which represents the measurement model at time t_k

(i) The prediction equations:

$$\hat{x}^-_k = F_{k,k-1}\, \hat{x}_{k-1}$$
$$Q^-_k = F_{k,k-1} Q_{k-1} F^T_{k,k-1} + Q_e$$

(ii) The filtering equations:

$$\hat{x}_k = \hat{x}^-_k + K_k(y_k - H_k\, \hat{x}^-_k)$$
$$Q_k = (I - K_k\, H_k) Q^-_k (I - K_k H_k)^T + K Q_y K^T$$
$$K_k = Q^-_k\, H_k^T\, (H_k Q^-_k\, H^T_k + Q_y)^{-1}$$

Where;
$\hat{x}^-_k$ is the predicted estimate of the state vector at time t_k,
$\hat{x}_{k-1}$ is the filtered estimate of the state vector at time t_{k-1},
Q^-_k is the covariance matrix of the predicted state vector,
Q_e is the covariance matrix of the dynamic model noise.
Q_k is the covariance matrix of the filtered state vector.
K_k is the gain matrix.