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Sensitivity and analysis GPS signals based bridge damage using GPS observations and wavelet transform

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ABSTRACT

This paper uses GPS monitoring system on the Yonghe Bridge. After a year from re-construction of this bridge, cracks were pronounced 48.2 m far from the beginning of the abutment. To analyze the movements of bridge tower, the current operational safety, the cause of bridge cracks and sensitivity of GPS signals, and its movements were observed under different stress factors such as wind speed, temperature change and traffic loads. The observed lateral, longitudinal of bridge's towers were studied. Two analytical methods namely; DWT and FT were used for the analysis of observation data. The analysis of test results indicates that: (1) The STFT is a significant step forward from the traditional FFT in terms of structural response analysis. (2) The sensitivity of GPS signals does not depend on the position of GPS antenna; and (3) the cracks of bridge deck bring out the frequency of the bridge tower movement transient characteristics.

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1. Introduction

Global Positioning System (GPS) technique has become an established technique in geodesy and surveying where it can provide position information with accuracies to a few millimeters. The measurement principle works worldwide, continuously and under all meteorological conditions, and therefore holds promise as a way to monitor the movement of structures. Successive generations of GPS receiver modules have seen a constant diminution of size, power consumption and cost. This allows building sizeable networks of autonomous GPS measuring stations with a relatively modest investment [17]. Many researches used the GPS technique in structural health monitoring (SHM), see [1–3,5,15,17]. Bridges are one of the important infrastructures in the national economy, which are considered the crucial links in transport network. Many bridge failures caused by normal or abnormal loadings. Monitoring the bridge deformation is the vital task in bridge maintenance and management. The process of implementing a damage identification strategy for aerospace, civil and mechanical engineering infrastructure is referred to as SHM.

Traditional spectral analysis methods such as the Fourier transform (FT) tell us which frequency components are contained in a signal. However, they do not tell us at what time those frequency components are present in the signal. This information is important in analyzing non-stationary signals, where the frequency content changes over time [12,13]. However, the wavelet analysis is suitable for analyzing signals records. Many researches and applications of describe analysis is available in deformation and damage processing [7–9,12,14,15]. Damage detection techniques based on wavelet analysis typically utilize measured structural responses and follow one of two approaches. In the first approach, Discrete Wavelet Transform (DWT) is tuned to detect abrupt changes in the response by decomposing the signal into approximation and detail levels. In detail level, decompositions correspond to abrupt changes in the response that might be associated with structural damage [8]. In the second

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approach, continuous wavelet transforms detect changes in the structure's natural frequencies by generating a time–frequency (Short Time FT (STFT)) map of the response signal and it is more suitable for analyzing non-stationary signal records, such as those with discontinuities or sudden [8,10,12,14,15].

However, this paper is extension of the researches [2,3,5]. The objectives of this research are: (1) To examine the GPS technique in movement monitoring and sensitivity it due to damage of the bridge tower; (2) To use and estimate the wavelet analysis in GPS signal processing and the damage time of bridge; (3) To study the reasons affecting bridge damage.

2. Descriptions and SHM system of bridge

The Tianjin Yonghe Bridge is one of the earliest cable-stayed bridges constructed in main land China as shown in Fig. 1. It comprises a main span of 260 m and two side spans of 25.15 and 99.85 m each. This bridge was opened to traffic in December 1987. Its girder was damaged after 19-years of operation and then was repaired and rehabilitated in 2007. As for the repair and rehabilitation, the girder over the mid-span was re-casted, other segments were repaired and rehabilitated by bonding carbon fiber reinforced polymer sheet to the surface of the girder. At the same time, all stay cables were replaced. A sophisticated long-term structural health monitoring system has been designed and implemented on this bridge during its rehabilitation. The system includes optical fiber Bragg-grating strain sensors, which were embedded into the re-casted segment of the girders, welded on the surface of rehabilitated segments of the girders, and embedded into cables. Six uniaxial accelerometers were attached on the cable to identify tension forces of the cables based on vibration analysis techniques. Two electromagnetic sensors were attached to two cables for measurement of cable forces. Fourteen uniaxial accelerometers were permanently installed on the deck of main span and two sides. Three GPS's and one biaxial accelerometer were monitored the towers movements (Figs. 1 and 2).

The GPS's were permanently installed on the two tower 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. In addition, 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. The double-frequency GPS receivers used were LEICA

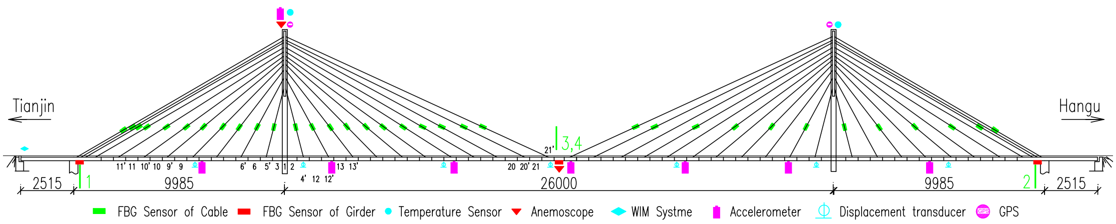

Fig. 1. Elevation and position of sensors for the Tianjin Yonghe Bridge.

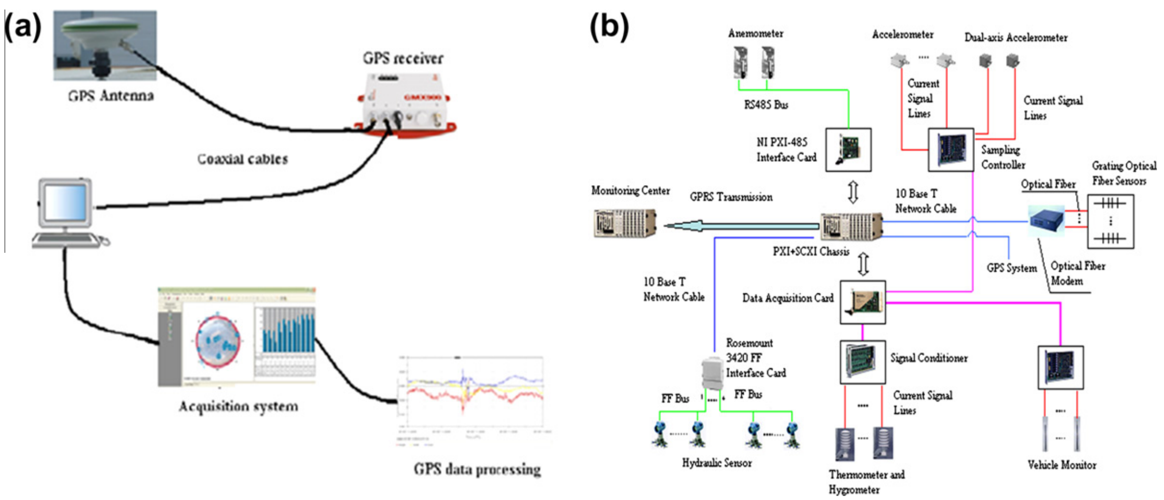

Fig. 2. (a) GPS network architecture and (b) The SHM system of Yonghe Bridge.

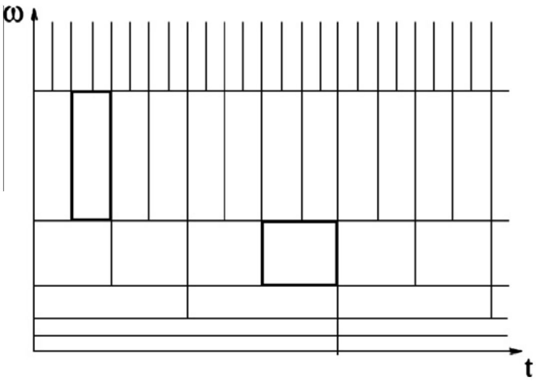

Fig. 3. Time–frequency plane.

GMX902 antenna (Fig. 2a). The satellite elevation cut-off angle is 13°, at least 9 satellites. The reference station refreshes the RTK correction messages for the GPS monitoring stations with a frequency of 20 Hz on each direction. Due to the large data files, the sessions were split into every one hour for processing purposes. The data collected were mixed with that generated by the receivers' own oscillators, and then processed using the Spider 2.1 RTK software, more details in [2,5].

3. Movement analysis and damage-based GPS signals

3.1. Wavelet analysis

Wavelet analysis is multi-resolution analysis in time and frequency domain, and is the important milestone of the Fourier Transform. Wavelet function $\psi(t)$ is called mother wavelet, which has shock properties and can reduce zero rapidly. It can be defined as $\int_{-\infty}^{+\infty}\psi(t)dt = 0$ mathematically. $\psi_{a,b}(t)$ can be acquired through compressing and expanding $\psi(t)$ [14,19]:

$$\psi_{a,b}(t) = |a|^{-1/2}\psi\left(\frac{t-b}{a}\right) \quad b \in R,\ a \in R,\ a \neq 0 \tag{1}$$

where $\psi_{a,b}(t)$ is successive wavelet; a is scale or frequency factor, b is time factor; R is the domain of real number. If $\psi_{a,b}(t)$ satisfies Eq. (1), for the energy finite signal or time series $f(t) \in L^2(R)$, successive wavelet transform of $f(t)$ is defined as [19,20]:

$$W_\psi f(a,b) \leqslant f, \psi_{a,b} \geqslant |a|^{-\frac{1}{2}} \int_R f(t)\bar{\psi}\left(\frac{t-b}{a}\right)dt \tag{2}$$

where $\bar{\psi}(t)$ is complex conjugate functions of $\psi(t)$. Eq. (2) describes that wavelet transform is the decomposition of $f(t)$ under different resolution level (scale). In other words,

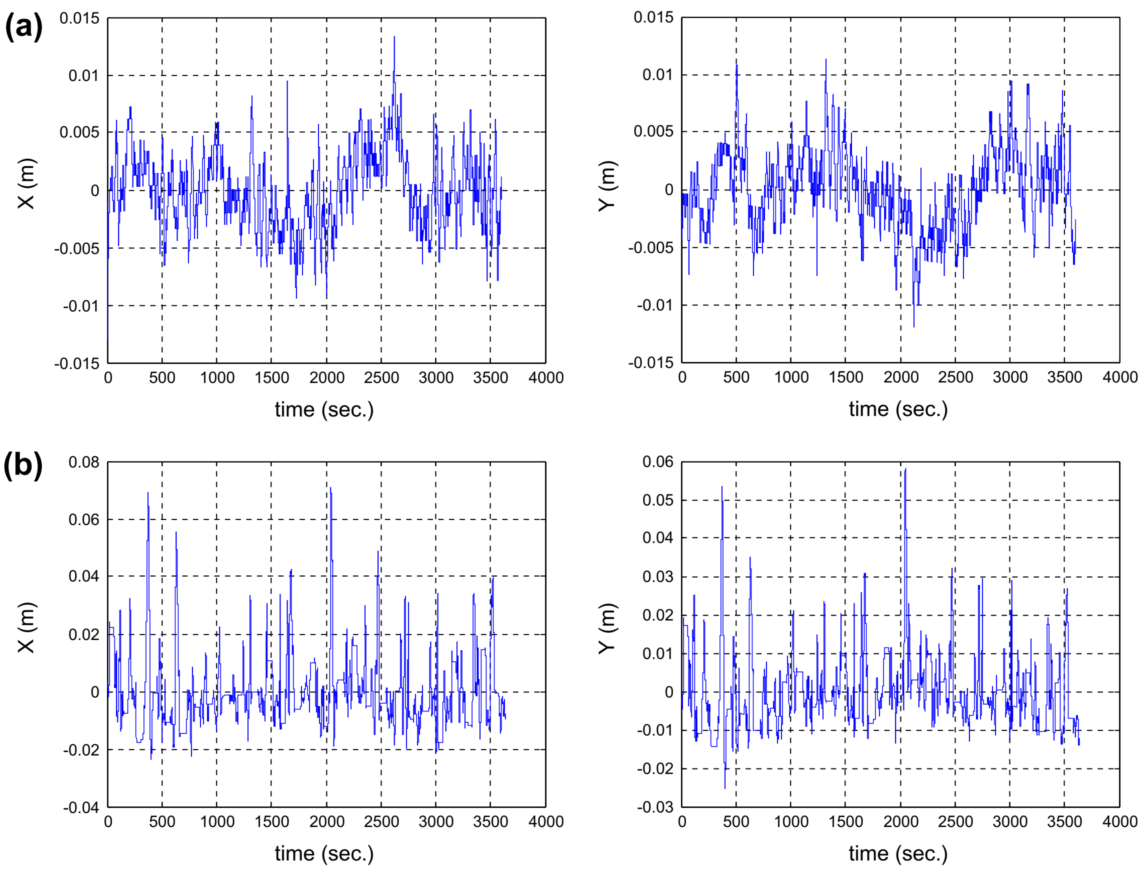

Fig. 4. Movements of southern tower in X (longitudinal) and Y (lateral) directions (a) unload case (June 2007) and (b) damage case (June 2008).

Table 1
The movement observations relative to June 2007.

Time index	*X*-movement (cm)	*Y*-movement (cm)
August 2007	0.291 ± 1.0292	-0.121 ± 0.8276
October 2007	2.63 ± 0.8949	2.37 ± 0.6765
November 2007	3.25 ± 0.7415	2.52 ± 0.6345
December 2007	4.16 ± 0.8426	2.90 ± 0.6140
January 2008	7.24 ± 0.6231	5.73 ± 0.5381
February 2008	8.44 ± 0.7566	5.70 ± 0.6278
March 2008	4.67 ± 0.7893	3.33 ± 0.6408
April 2008	3.62 ± 1.1824	2.61 ± 1.0482
May 2008	0.689 ± 1.3429	0.384 ± 1.0789
June 2008	–0.623 ± 0.6966	0.395 ± 0.4574
August 2008	1.81 ± 0.3398	1.77 ± 0.3885

the essence of wavelet transform is to filter wave for *f*(*t*) with different filter.

In real application successive wavelet is often discrete. Let $a = a_0^j, b = kb_0a_0^j$, $a_0 > 1$, $b_0 \in R$, *k*, *j* are integer number. DWT of *f*(*t*) is written as [19]:

$$W_\psi f(j,k) = a_0^{-j/2}\int_R f(t)\bar{\psi}\left(a_0^{-j}t - kb_0\right)dt \qquad (3)$$

When $a_0 = 2$, $b_0 = 1$, Eq. (18) becomes binary wavelet transform [19]:

$$W_\psi f(j,k) = 2^{-j/2}\int_R f(t)\bar{\psi}(2^{-j}t - k)dt \qquad (4)$$

$W_\psi f(a, b)$ or $W_\psi f(j, k)$ can reflect the characteristics of original time series in frequency (*a* or *j*) and time domain (*b* or *k*) at the same time. When *a* or *j* is small, the frequency resolution of wavelet transform is low, but the time domain resolution is high. When *a* or *j* becomes large, the frequency resolution of wavelet transform is high, but the time domain resolution is low. That is, wavelet analysis is a mathematic microscope. In real world observed time series are discrete, such as deformation process and earthquake process. So DWT must be selected for decomposition and re-construction of time series [1,6]. There are many DWT algorithms in MATLAB tools [4,20].

The difference between this WT and windowed FT lies in the shapes of analyzing function W_ψ and $\psi_{a,b}$. The functions W_ψ all consist of the same envelope function g irrespective of the center frequencies of the windows [21]. In contrast, the $\psi_{a,b}$ functions have time-widths adapted to their frequency [21], see Fig. 3. Kitada concluded that the

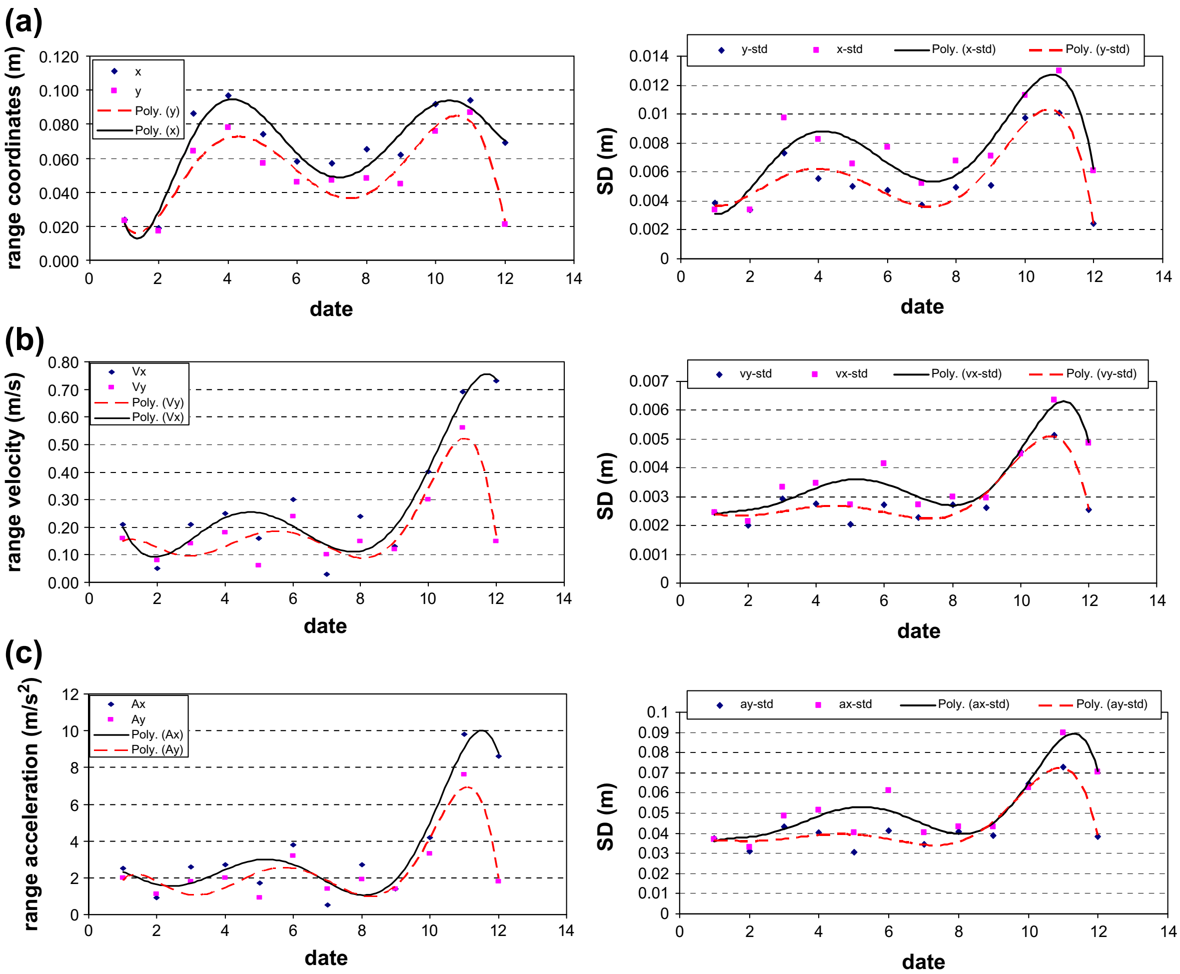

Fig. 5. Statistical analysis of (a) GPS observation, (b) Velocity converted and (c) Acceleration converted, from GPS signals.

Table 2
Summary of environmental observations with time selections.

Time index	Wind		Temperature		
	Mean speed (m/s)	Mostly direction (Deg.)	Max. (°C)	Min. (°C)	δ (mm)
June 2007	–	–	–	–	–
August 2007	2.821	150	19.238	18.201	0.778
October 2007	1.471	30–60	9.381	7.825	1.167
November 2007	1.137	250	−1.483	−2.948	1.098
December 2007	0.811	220–260	−0.72	−2.094	1.031
January 2008	4.685	140–160	−6.396	−8.746	1.762
February 2008	3.875	150	−5.908	−8.563	1.991
March 2008	1.113	50–100	1.965	0.836	0.847
April 2008	4.321	20–350	7.397	6.238	0.869
May 2008	3.535	42–48	21.436	19.879	1.168
June 2008	–	–	–	–	–
August 2008	–	–	21.893	20.612	0.961

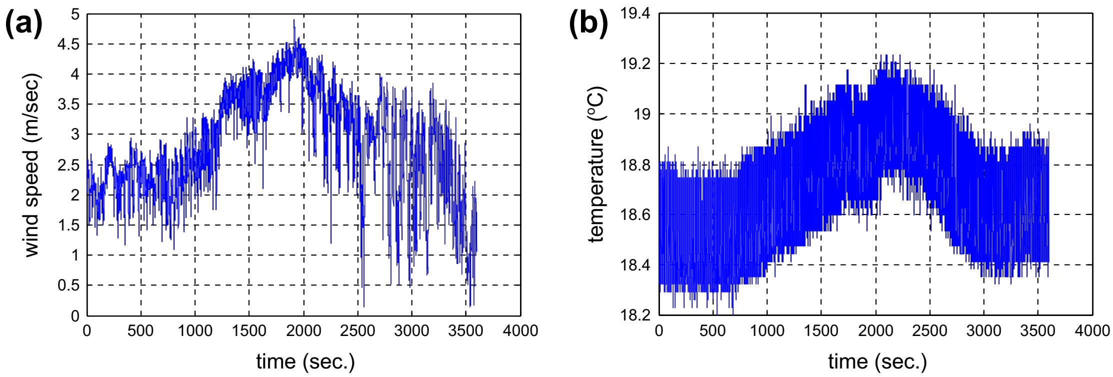

Fig. 6. Sample environmental observation (a) wind speed and (b) temperature in August 2007.

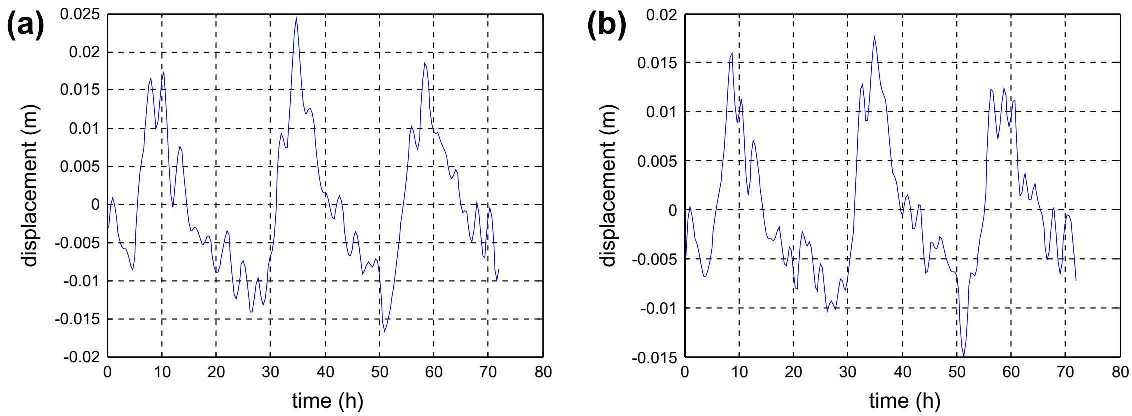

Fig. 7. Mean 20-min displacement for southern tower in (a) X and (b) *Y*-directions.

WT is better able to zoom in on very short-lived, high frequency phenomena than the windowed FT [21].

Also, Patsias and Staszewski [11] showed the possible use of the WT in developing a damage detection method for optically observed mode shapes. Companion information is produced from the WT of mode shapes: the displacement mode shape comes from the approximation signals and the damage location comes from the detail signals. However, a DWT tools in MATLAB has been adopted in this research to analyze the wavelet coefficient of GPS signals to detection the displacement and damage of bridge.

In addition the phase plane, formed by time and frequency, the frequencies can be displayed on a two-dimensional time–frequency plane that is called a STFT. It is possible to identify the energy content of the signal

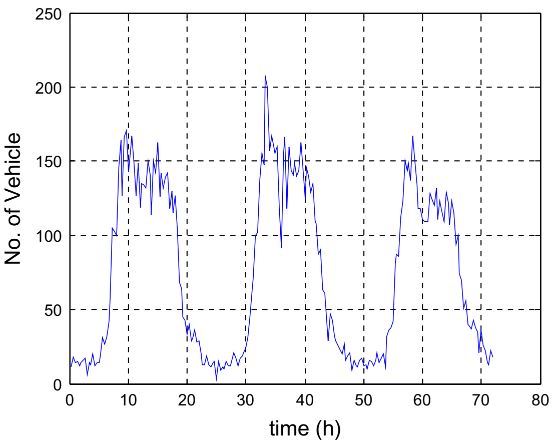

Fig. 8. Variation in number of vehicle during the observation.

at different frequencies. The STFT was essentially applying FFT with a short moving time window repeatedly to a short time series to obtain its time–frequency representation. To represent the signal with more detail in the time domain, we have to make the time window smaller. If the sampling rate of the signal remains the same, the method of choosing a smaller time window makes the frequency resolution worse. So a good resolution in the time and frequency domains cannot be achieved at the same time [15]. So in this paper, the ***spectrogram*** MATLAB code was used with smaller Hamming window after pr-processing to analyze the time frequency plane domain.

3.2. Statistical movement analysis

Structural analysis is required to determine whether significant movements occurred between the monitoring campaigns or not. Geometric modeling is used to analyze spatial displacements. General movement trends are described using a sufficient number of discrete point displacements dn $(\Delta x, \Delta y, \Delta z)$ 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 [16].

$$|dn| < (e_n) \quad (5)$$

where, dn 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 [16]:

$$e_n = 1.96\sqrt{\sigma_f^2 + \sigma_i^2} \quad (6)$$

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 $|dn| < (e_n)$ the point is not moved, else the point is moved [16].

4. Results and discussions

4.1. Observations analysis

As the tower in the Tianjin side of the Yonghe Bridge (Southern Tower) in two directions were observed at the same time intervals, it is possible to compare the movements of this tower. The evaluation of observations was performed using BCS and the observation initiation times are shown as reference in the graphics to interpret better the changes. The longitudinal movements of the tower on the traffic flow (Y-direction) demonstrate an increase starting from the initiation of observation until January 2008 (5.73 cm) and later on, a decrease is seen in this movement (Fig. 4 and Table 1). The lateral movements of the tower on the Tianjin side (X-direction) demonstrate an increase starting from the initiation of observation until February 2008 and later on, a decrease is seen, the change being 8.44 cm (Table 1). Accordingly, it can be concluded that the lateral and longitudinal movements of the towers are similar quarters, approximately. This indicates that the movements of tower in two directions are correlated (Fig. 5).

From Table 1 and applied Eqs. (5), (6), it can be seen that the tower moved in-between October 2007 to May 2008 and return moved after June 2008. The following Figures summarize the displacements range of tower and velocity, acceleration converted range by integration of movements, in addition the Standard Deviation (SD) of these observations and converted results. Whereas, the range is the difference between the highest and lowest value in the data set given by ($\Delta X = X_{\max} - X_{\min}$).

Fig. 9. Cracks shape of (a) Deck near abutment (48.2 m from Tianjin bridge side), (b) Tower, and (c) Deck near mid-span of bridge.

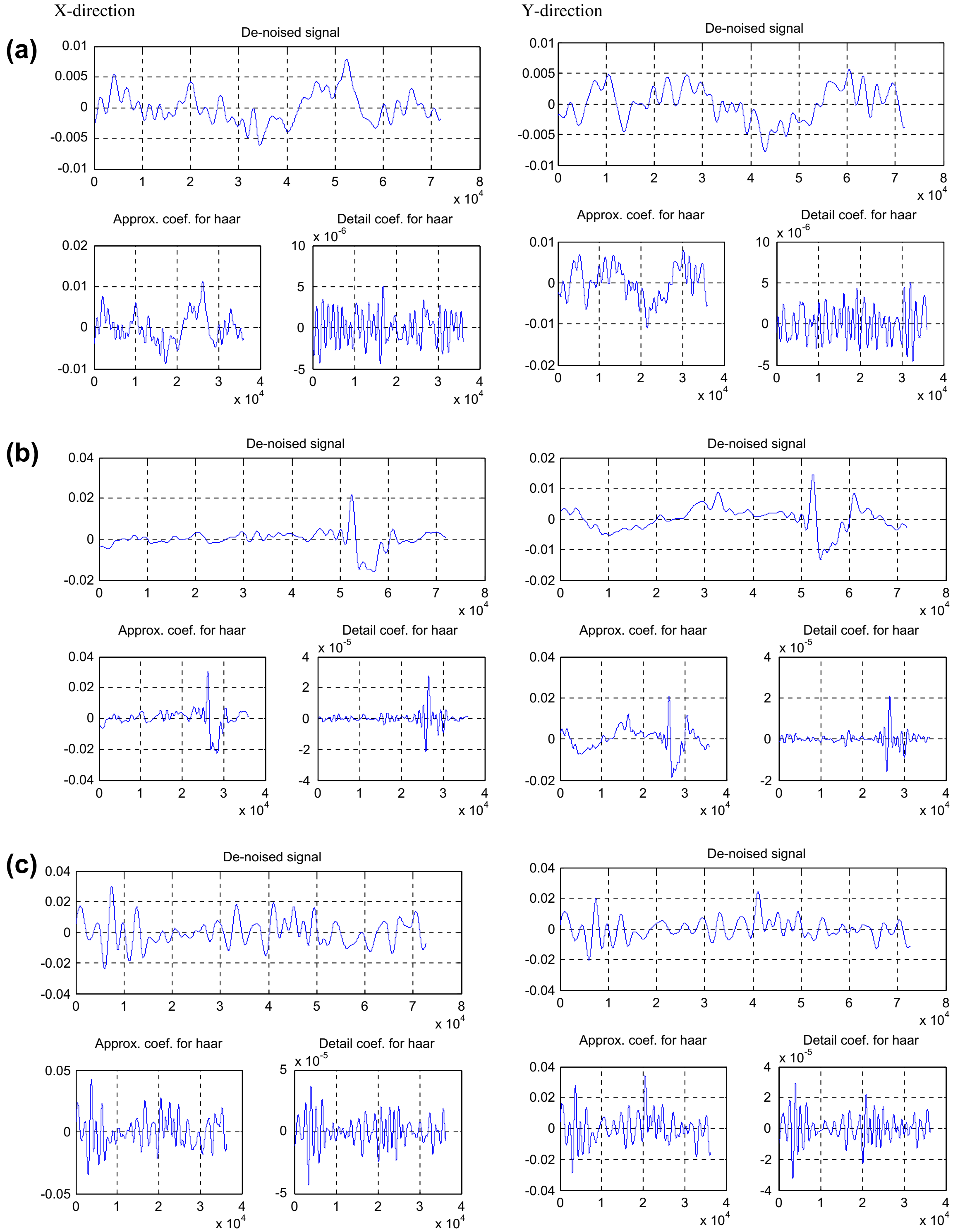

Fig. 10. The de-noised and coefficient for Haar wavelet analysis in *X* and *Y*-directions at (a) unload case (June 2007), (b) load case (December 2007), and (c) damage case (June 2008).

From these figures, it is shown that the velocity and acceleration converted range revealed that the damage of bridge may have occurred in-between May and July 2008. The GPS displacements range cannot reveal the

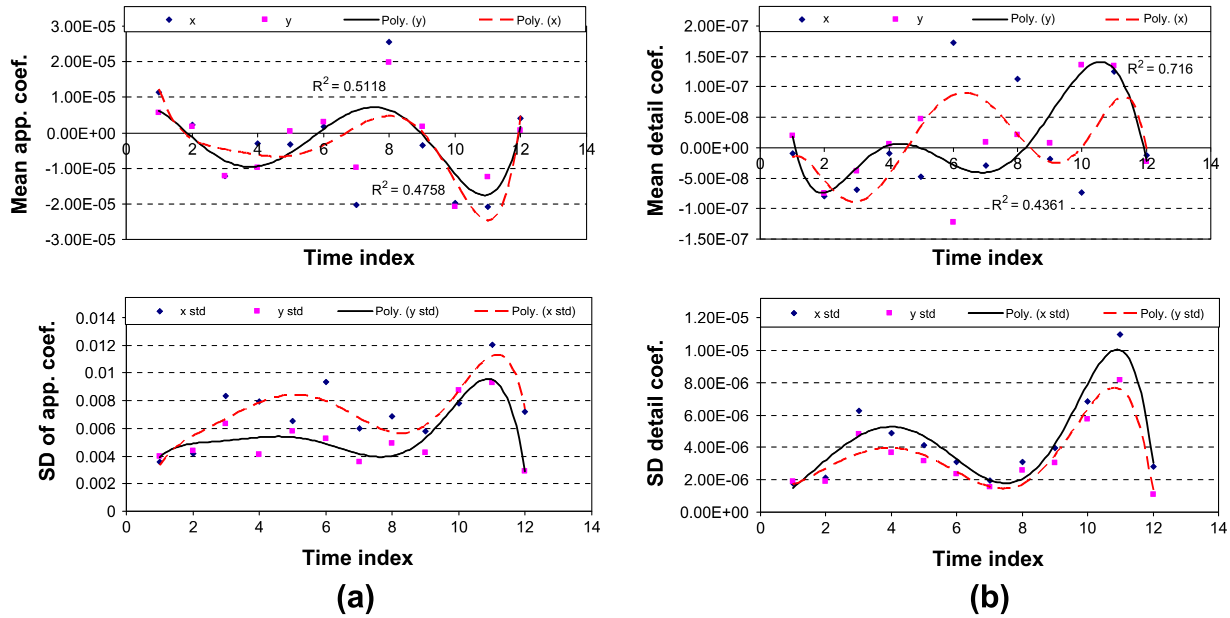

Fig. 11. Statistical mean and STD of the (a) approximate and (b) detail for the Haar wavelet coefficients with the time monitoring.

damage of bridge. In addition, the SD of observations, velocity and acceleration converted may be near shape of fit polynomial and revealed to the time damage of bridge.

The wind and temperature having effects on the bridge during the period of observations are given in Table 2. The deformation tower bridge due to temperature is calculated as Eq. (7) [18].

$$\delta = \alpha \cdot \Delta T \cdot H \tag{7}$$

where δ is deformation of tower due to temperature, α is Coefficient of thermal expansion (12 × 10–6/°C), H is height of the tower (62.5 m) and ΔT is change in temperature.

During the observation periods of the tower, the deflections due to temperature changed in the bridge tower are not very large. The temperature change decreased between the initiation of observation until January 2008, then there were increases as shown in Table 2. On the other hand, in the same time span from the commencement of the observations until December 2007 the wind speed decreased significantly, then increased in January 2008, and then changed in-between decreasing and increasing after this date. The wind direction changed as shown in Table 2 with the observation period. To study the effect of traffic loads, three days of continuous measurement of GPS and number of vehicles were used, which were from 0:00 of January 10, 2008 to 24:00 of January 12, 2008, whereas the traffic observations are not available on the other observations date. The averages of all observations in the 20-min segment are plotted in Fig. 7 (after de-noised signals) and Fig. 8.

From these figs., it can be seen that the correlation between movements of southern tower and number of vehicles are 0.98 and 0.97 with X and Y-directions, respectively. In addition, it is revealed that the sensitivity of GPS signals increased with the traffic loads movements on the bridge. This revealed that the traffic loads are the main reason of tower movements and damage deck of bridge. From Tables 1 and 2 and Figs. 6–8 summarized that the effectiveness of temperature are very low with the time observations. In addition, the wind loads may have affected sometime on the movements of bridge tower but mostly it is not the main reason of movements of tower and the traffic loads are the main reason of movements and cracks in the tower and bridge deck (Fig. 9).

These photos (Fig. 9) revealed that the cracks ***a*** may be due to shear force, cracks ***b*** and ***c*** may be due to bending moments. So, the movements of towers as shown in Table 1 probable tension forces in the bridge cables may have occurred which affect by a shear force on the deck of bridge. And the increase in traffic loads acting on the bridge with time increased the moments on the bridge mid-span. Herein, we can conclude that the traffic loads are the main reason of cracks of bridge, so recommended that the traffic loads must be decreased on the studied bridge.

4.2. Wavelet analysis

Figs. 10 and 11 show some of the de-noised time series residuals and the mean and SD of wavelet coefficients at southern original GPS signals deformation. These signals were collected from June 2007 to August 2008. All observation data were collected from 12.00 PM to 1.00 PM for local time of China. The residuals of the signals are obtained through the detrend code from MATLAB at each time of monitoring.

The DWT was computed for each case using MATLAB Wavelet Toolbox. Haar wavelet was used for all the analyses. The DWT Figs. show the de-noised of the considered case. At the top of each figure, the de-noised is

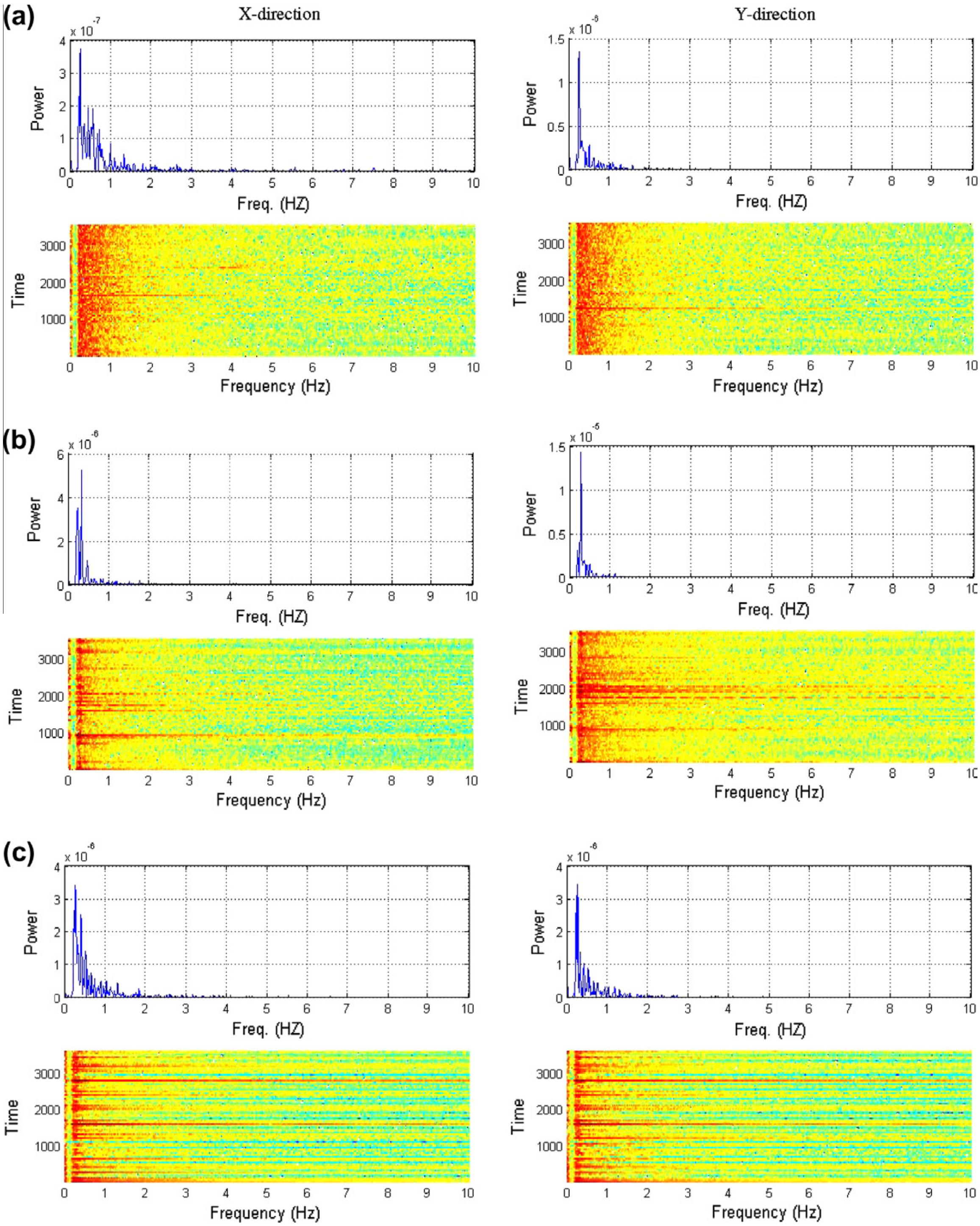

Fig. 12. One and two-dimensional frequency for the tower movement in X and Y-direction at (a) June 2007, (b) May 2008 and (c) June 2008 (the continuous red color revealed to the high power). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

plotted. Beneath, the low-level approximation signal (a) is displayed. And, the high-level detail signals (d) are shown. In Fig. 11, applied sixth degree polynomial is presented.

These figures can be considered showing the healthy bridge. According to these Figs, clear range oscillations appear in the signals with the time index, as the severity of the fault increases to damage case. Fig. 10a shows the

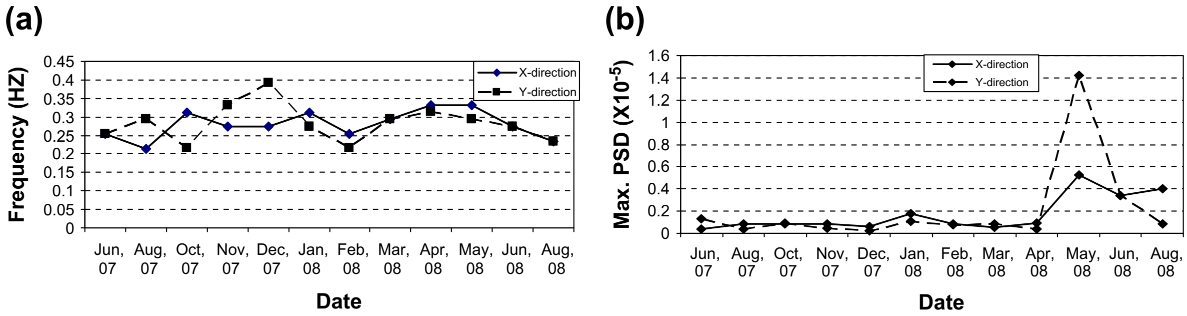

Fig. 13. (a) The first mode frequency and (b) the maximum PSD of the first mode for the GPS signals.

high-level signals for the case of an un-loaded bridge. There can be also observed the clear oscillations in the signals b and c, as occurred for the loaded bridge. Furthermore, it can be observed that the pattern created by the eccentricity is totally different from that appearing in the case of damage, which is shown in Fig. 10c. These revealed that the sensitivity of GPS signals doesn't depend on the position of it. Also, the detail coefficients can refer to the effect of traffic loads on the bridge, whereas the oscillations in the signals due to traffic loads in Fig. 10a and b. while, they were due to traffic loads and damage effects in Fig. 10c and the results cited in Li et al. [3] and Kaloop, et al. [2,5]. Fig. 11 is statistical summary for the wavelet coefficient, from this figs., it can be seen that the maximum mean approximation coefficient at May and June 2008 (-2×10^{-5}), Fig. 11a, in addition the SD of the approximate coefficient signals are 0.012 and .009 in two directions in June 2008. Also, it can be shown that the same shapes of curves in the details curves, mean and SD, respectively. In addition, it can be seen that the mean detail coefficient in May and June 2008 at *Y*-direction is greater than it at *X*-direction. These results revealed that the damage of deck may have happened in May 2008.

Herein, it can be recommended that the increase of mean or range and SD the detail and approximate coefficients revealed that the damage would occur, so this technique can be used to predict the time damage detection. In addition, these results suggest that the performance of wavelet analysis for structural damage detection depends strongly on the excitation and restoring tower displacements. Clearly, the performance deteriorates as more realistic damage and traffic load effects. Fig. 12 shows the some results of one and two-dimensional frequency domain. Fig. 13a and b are summary the first mode frequency for the GPS signals at the same times above and the maximum power spectral density (PSD) with the time index, respectively.

The results explain that the high maximum powered frequencies for movements of tower in X and *Y*-directions are not the same. Besides, it can be seen that the high distortion frequency of towers in two directions happened after August 2007 till June 2008 and after that, and high frequency reactions of the south tower in the *X* and *Y*-directions are 0.332 HZ and 0.391 HZ in May 2008 and December 2007, respectively. Fig. 12 shows that the red frequency is not uniform along the time axis in June 2008. Also, the beginning ununiform red color is shown at May 2008, as shown in Fig. 12b. Beside that, from the results, it is shown that the red color returns uniform in August 2008. In addition, from Fig. 13a, it can be seen that the correlation between the frequencies in two directions is very low from traffic load affects to the damage occurred. Also, Fig. 13b revealed that the maximum PSD at May 2008 in X and *Y*-direction are 0.49 and 1.42, whereas, mostly can be shows that the maximum PSD in *X*-direction is greater than it in *Y*-direction, Fig. 13b. These results revealed that the beginning of damage may have happened in May 2008 and increased to June 2008. This indicates that the cracks of bridge deck bring out the frequency of the bridge tower movement transient characteristics. In addition, the STFT is a significant step forward from the traditional FFT in terms of structural response analysis. In addition, it was found that low frequency obtained from power spectrums reflected the expected damage time of the bridge.

5. Conclusions

In this study, we used the environmental, GPS observations and wavelet analysis to propose and analyze the movements and damage detection of Yonghe Bridge. Based on this limited study, the analysis of the results leads to the following findings:

1. The sensitivity of GPS signals is very high to the movements and damage of structures.
2. The damage of deck and cracks of tower occurred due to traffic loads.
3. The low frequency obtained from power spectrum density reflected the expected damage time of Yonghe Bridge.
4. The damage effect of Yonghe bridge happened in May 2008 and increased to June 2008 with the traffic loads effects.
5. The cracks of bridge deck bring out the frequency of the bridge tower movement transient character-istics.
6. The STFT is a significant step forward from the traditional FFT in terms of structural response analysis.
7. The increase of mean or range and SD the detail and approximate coefficients revealed that the damage would occur, so this technique can be used to predict the damage time detection.

8. The sensitivity of GPS signals doesn't depend on the position of GPS antenna.
9. The effectiveness of temperature is very low with the time observations, the wind may have effected sometime on the movements of tower.
10. The range of converted acceleration and velocity, and its SD revealed that the damage of the bridge may have occurred in-between May and July 2008.
11. The tower moved in-between October 2007 to May 2008, and it is returned to move after June 2008.

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