

# **DAMAGE DETECTION OF CABLE-STAYED BRIDGE USING COMBINED GPS AND ACCELEROMETER OBSERVATIONS**

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## **ABSTRACT**

The universe of damage detection scenarios likely to be encountered in realistic civil infrastructure applications is very broad and encompassing. Among the numerous considerations that influence the choice and effectiveness of a suitable method is studying the damage detection in both time and frequency domains. Nowadays, the use of a real time kinematic-global positioning system (RTK-GPS) and accelerometers sensors are capable of detecting the damage of long bridges. However, this study aims to use the integrated GPS/accelerometer observations to detect the damage effect of the cable-stayed Yonghe Bridge. 3-D finite element model (FEM) of the cable-stayed bridge was established to support the proposed bridge tower movement analysis. The results of the integrated GPS-accelerometer observations show very significant results for the damage detection using GPS observations in the time domain, while the accelerometer observations are more effective in damage detection in the frequency domain analysis. In addition, the traffic loads are the main effective load on the bridge behavior and safety.

## **KEYWORDS**

Cable-stayed bridge, FEM, GPS, accelerometer, damage detection, frequency domain.

## **INTRODUCTION**

Increased awareness of the economic and social effects of aging, deterioration and extreme events on civil infrastructure has been accompanied by recognition of the need for advanced structural health monitoring (SHM) and damage detection tools (Chang et al. 2003). The integrated analysis were foster the development of practicable SHM methodologies as well as the discovery of new physical knowledge in the area of deterioration (sudden or progressive) of civil infrastructure systems (Elgamal et al. 2003). Monitoring bridge deformation and damage detection is of great importance for maintenance bridge safety (Roberts et al. 2004).

In recent years, efforts have been made to use an integrated monitoring system consisting dual frequency Global Positioning System (GPS) receivers and accelerometers for the detection of the dynamic of structures (Roberts et al. 2004; Meng et al. 2007; Li et al. 2006; Hwang et al. 2012). The Integration of an accelerometer with the GPS could significantly increase the measurement production and improve the overall system reliability and performance of structures (Meng et al. 2007). Furthermore, Li et al. 2006 concluded that the integrated system comprising of GPS and

accelerometers has been developed with the objective of assessing full-scale structural responses by exploiting the complementary characteristics of GPS and accelerometer sensors.

Sohn et al. 2004 concluded that the basis for damage detection appears intuitive; its actual application many significant technical challenges. The most fundamental challenge is the fact that damage is typically a local phenomenon and may not significantly influence the lower frequency global response of a structure that is normally measured during vibration tests. Environmental and operational variations, such as varying temperature, moisture, and loading conditions affecting the dynamic response of the structures cannot be overlooked either. The change of the bridge's fundamental frequency is proportional to its stiffness; the decrease of the frequency is expected as the damage progresses.

Herein, the accelerometers (with range  $\pm 2$  g and sensitivity of  $5 \times 10^{-5}$  g) and real time kinematic (RTK)-GPS technique were used in the integration to detect the damage of the Yonghe bridge, China. The receivers, which used are LEICA GMX902 antenna (20 Hz data rate, accuracy of 1mm+0.5ppm (horizontal)) and observation data was pre-processed in the WGS84 coordinate system using the software GPS Spider 2.1. In addition, the FEM are widely carried out to assist the structure design. The FEM of the cable-stayed Yonghe Bridge was modeled based on the engineering drawings and the bridge modal frequencies were used to support the GPS/accelerometer integration results. However, the focus of this paper is on the methodology aspects for the damage detection of Yonghe cable-stayed bridge. GPS and accelerometer observations in two monitoring cases: before and after the damage occurrence are processed by using different analytical approaches. This study is concerned in studying the behavior of the southern bridge tower, which is located in the Tianjin city side.

## **BRIDGE DESCRIPTION AND SHM SYSTEM**

The Yonghe Bridge is a cable-stayed bridge, which was constructed and opened to traffic in December 1987; it consists of a main span of approximately 260m, two side spans of 125m each with total length of 510 m. The two door-shaped towers are reinforced concrete members with total height of 60.50 m. The bridge deck consists of precast concrete box girder segments and transverse beams with approximate spacing of 2.90 m, carrying two traffic lanes with total width of 14.50 m. The cable-stayed Yonghe Bridge general view is shown in Figure 1.



Figure 1 Yonghe Bridge southern tower general view

After 19 years of operation, cracks with a maximum width of 2 cm were observed at the bottom of a girder segment over the mid-span of the bridge deck. Repairs were conducted between the years 2005 and 2007; the girder over the mid-span was re-casted in situ and all of the bridge cables were replaced. The bridge SHM system general layout is shown in Figure 2. The SHM system contains fiber Bragg-grating strain sensors, six uni-axial accelerometers were attached to the cables to identify the tension forces of the cables based on vibration analysis techniques. In addition, two electromagnetic sensors were attached to the cables for cable forces measurement. Furthermore, fourteen uni-axial accelerometers and one bi-axial accelerometer were permanently installed on the bridge deck of the main span and two side spans, and one on tower top point. Moreover, an anemoscope was attached to the tower top to measure the wind velocity. Additionally, a temperature sensor was installed at the bridge mid-span to measure the ambient temperature. Finally, three GPS units were used; the GPS units were permanently installed on the two towers top points and on the riverbank near the bridge as a base point. For the output of the GPS software was the time series of the instantaneous Cartesian coordinates of the rover receiver in the WGS84 coordinate system. A local bridge coordinate system was established to be used in the analysis and evaluation of the observed data (Roberts et al. 2004). The analysis was based on the data collected and converted to a local bridge coordinate system (BCS) in the X (which shows the lateral direction for the local BCS) and Y (which shows the longitudinal direction for the local BCS)-directions, whereas the movements in these directions were greater than in Z-direction, thus the data in Z-direction was declined.

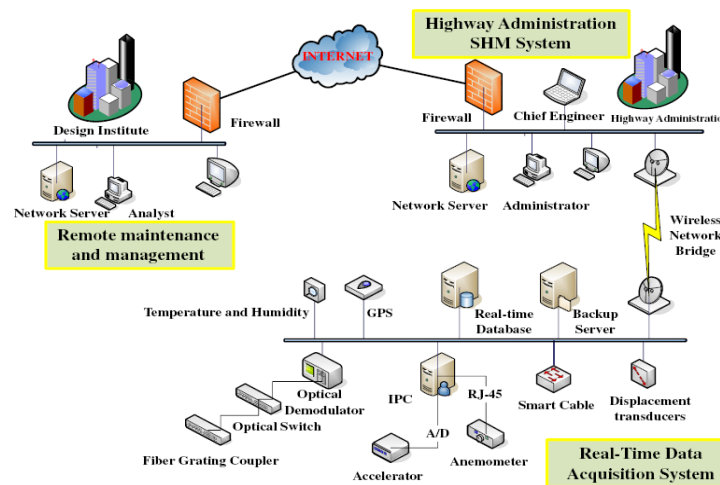


Figure 2 The structural health monitoring system general layout

## BRIDGE DAMAGE HISTORY

On August 2008, several damage patterns were detected during an inspection of the bridge (Li et al. 2013), many cracks and concrete failure were detected in the bridge deck and tower as shown in Figure 3. The measured and observed data of the bridge tower using GPS and accelerometers are used to monitor and assess the ability of various SHM methods to detect, localize, and quantify these damage patterns. The damage patterns, especially the degrees of damage, were considered to have developed gradually over time. Fortunately, accelerations observations using

the accelerometer were measured from January to August 2008, when the bridge was presumably damaged gradually by overloading. The integrated GPS and accelerometer observations are studied and analyzed in two mentoring conditions; before the bridge damage occurrence, which is represented by the observations on January 17, and after the bridge damage, which is represented by the observations on July 31. Therefore, damage detection was studied on this paper based on sensitivity of southern bridge tower movements due to damage effects.

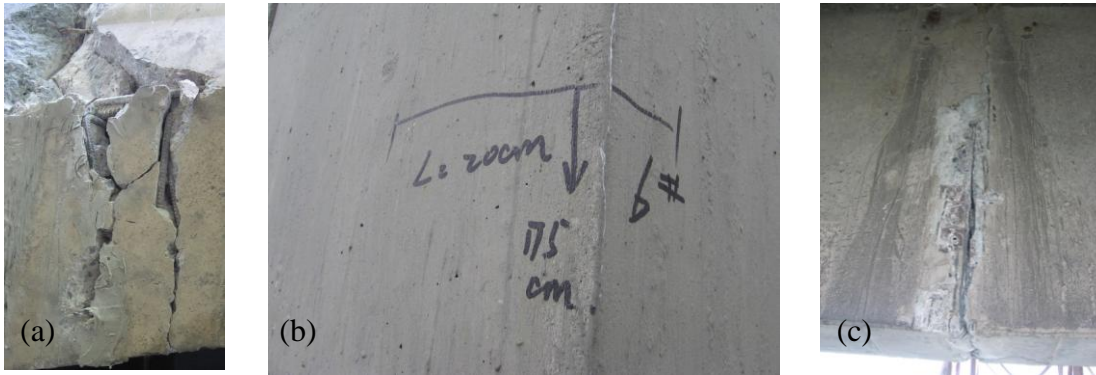


Figure 3 Bridge concrete damage and cracks shape

### BRIDGE FINITE ELEMENT MODEL

A three-dimensional FEM of the cable-stayed Yonghe Bridge was modeled based on the engineering drawings and implemented using the SAP2000 software. Both of the bridge towers with height 60.50 m and the main girder with width 14.50 m and with total length 510.00 m are modeled using the beam elements. Transverse concrete beams with approximate spacing of 2.90 m are added to the model as additional mass elements. 88-cable elements are used to model all the bridge cables. In addition, additional secondary uniform dead load is added to consider all the secondary loads on the bridge main girder. The main girder is modeled as floating on the bridge towers and both of the towers are fixed to the ground. The bridge FEM, the first and second mode shapes and modal frequencies are shown in Figure 4.

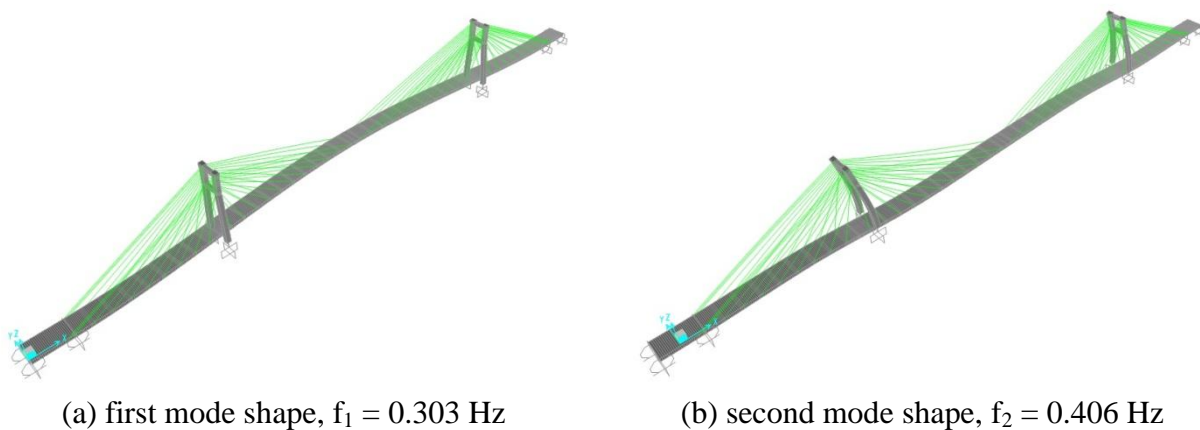


Figure 4 First and second mode shapes of the Yonghe Bridge finite element model

## **METHODOLOGY AND DATA ANALYSIS**

Many studies focused on the Yonghe Bridge analysis and behavior, for instance some of these studies summarized the effective loads on the bridge movements (Kaloop and Li 2009; Li et al. 2010). While other studies focused on the damage detection based on the bridge deck accelerometers measurement analysis (Li et al. 2012; Li et al. 2013) or tower GPS measurement analysis (Kaloop and Li 2011). However, this study is focused on the cracks and damage detection based on the integration of both GPS and accelerometer observations, which are located on bridge southern tower. The Yonghe Bridge cracks and damage detection based on the southern tower observation analysis in both X- and Y-direction is presented in this study. The integration of GPS/accelerometer sensors in both time and frequency domain is presented. The GPS and accelerometers observation data was collect on January 17 and July 31, 2008 that represent the two monitoring conditions: before and after the damage and cracks occurrence, to analyze and assess the bride damage effects on the bridge tower movements.

### ***GPS/Accelerometer Observations Data Filtering***

From previous studies (Meng et al. 2007; Moschas and Stiros 2011; 2013), it is known that the time series of GPS displacement calculations is contaminated by noise. Therefore, filters should be used to extract the displacement components of the time series (Moschas and Stiros 2011). The similarity transformation was used to extract the time series of both X- and Y-direction displacement relative zero representing the equilibrium level of the monitoring point (Moschas and Stiros 2011). In this study, the Moving Average (MA) filter is used to de-noise the GPS observation data and to extract the relative displacements of the bridge tower in both directions. In addition, band-pass and MA filters are applied together to the GPS observations to extract bridge tower dynamic displacement component in the two monitoring cases: before and after the damage and cracks occurrence. Figure 5 shows the bridge tower dynamic displacement component before and after applying the data filters. Whereas, the bridge tower dynamic displacements are derived from the double integration of the acceleration time histories from the accelerometer observations using the band-pass filter to eliminate the high frequency noises of the acceleration observations.

### ***GPS/Accelerometer Frequency Identification***

The transformation of the GPS and accelerometer observations from the time domain to the frequency domain is performed by applying the Fast Fourier Transform (FFT) (Li et al. 2006). In addition, the power spectrums for frequencies components of the time series were calculated. Figure 7 shows the fundamental frequencies of the both GPS and accelerometer acceleration observations in the two horizontal directions. In addition, the double differentiation procedure is used to convert the GPS displacement observations in the X- and Y-directions to acceleration time series (Moschas and Stiros 2013). Moreover, the fundamental frequencies of the calculated GPS acceleration time histories are computed based on band-pass filter for the 24-hour observations for the two monitoring cases: before and after the damage and cracks occurrence as shown in Figure 7.

## RESULTS AND DISCUSSIONS

### GPS Quasi-Static Displacements

The bridge tower original and smoothed GPS observations using MA filter, also the dynamic displacement component of GPS observations of one-hour observations at 23:00 before and after the damage occurrence, on January 17 and July 31, are shown in Figure 5. From this Figure, it can be seen that the high GPS displacement amplitude of both original and smoothed observations is shown clear on July 31 due to the damage and cracks occurrence in the bridge. In addition, the correlation between original and smoothed data is very high with no displacement information losses in both dates. Accordingly, applying the MA filter combined with using the band-pass filter shows good results, and can be recommended to extract the bridge tower displacement components from GPS observations. Furthermore, it can also be drawn from the results that, the maximum quasi-static displacements are 16.0 and 9.8 mm, and the mean quasi-static displacements are  $2.1 \times 10^{-3}$  and  $0.4 \times 10^{-3}$  mm in the X- and Y- directions, respectively, on January 17. While, the maximum quasi-static displacements are 30.5 and 23.3 mm, and the mean quasi-static displacements are  $4.0 \times 10^{-3}$  and  $2.0 \times 10^{-3}$  mm in the X- and Y-directions, respectively, on July 31. Also, it is can be noticed that the maximum dynamic displacement component of the GPS observations are 1.8 and 1.2 mm, while the mean dynamic displacements are 0.06 and 0.05 mm for X- and Y- directions, respectively, on January 17. However, the maximum dynamic displacement components are 20.5 and 16.0 mm, while the mean dynamic displacements are 0.47 and 0.37 mm for X- and Y-directions, respectively, on July 31.

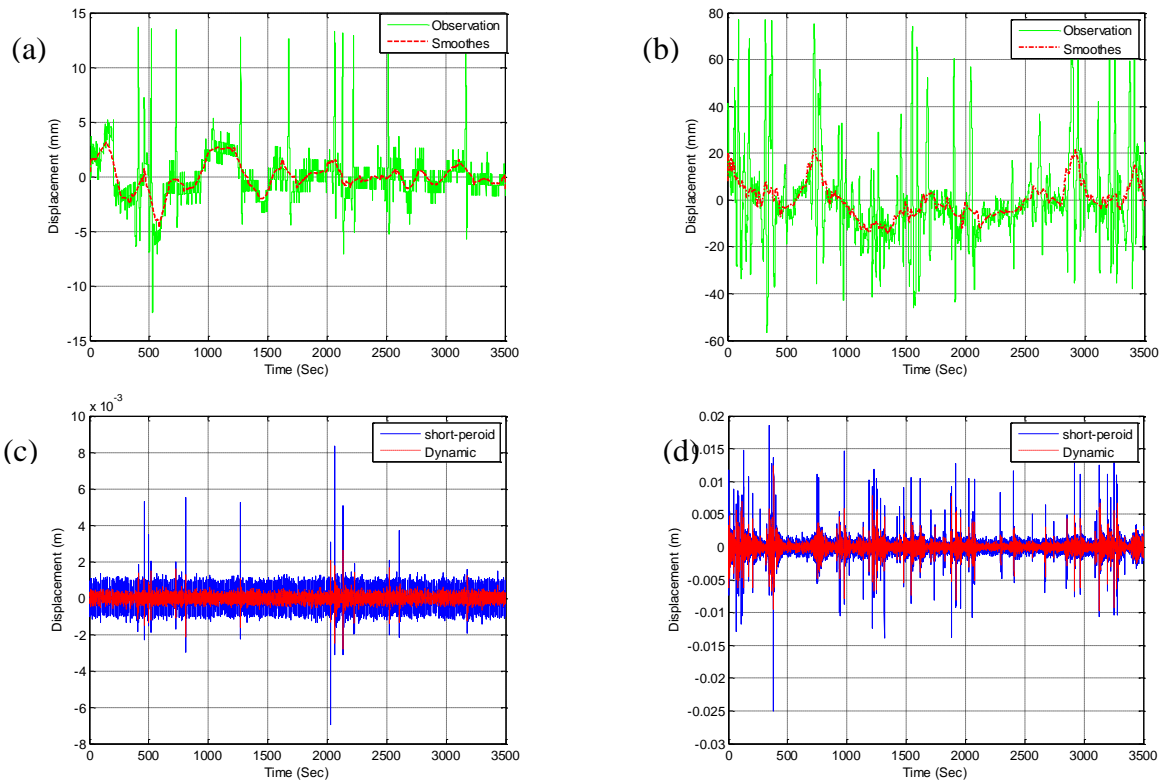


Figure 5 GPS observations and MA smoothing filter of one hour observations in Y-direction: (a) and (b) Original and smoothed GPS observations at 23:00 on January 17 and July 31; (c) and (d) dynamic displacement component of GPS observations at 23:00 on January 17 and July 31

The previous results show that due to the cracks and damage occurrence in the bridge, there is a change up to double in the maximum and mean values of the quasi-static GPS displacement component of the bridge tower in both horizontal directions. While, it is up to more than seven times in case of the maximum and mean values of the dynamic displacement component in both directions. This gives a confirmation that, although the bridge damage was located mainly in the bridge deck, but due to the bridge cables, which transfer the deck displacements and vibrations to the tower, the bridge tower suffers more displacements and vibrations after the damage occurrence appears in the high values of the dynamic GPS displacement component.

### *GPS/Accelerometer Dynamic Displacements*

Figure 6 shows the maximum dynamic displacement component of both GPS and accelerometer 24-hours observations of the bridge tower in both X- and Y-direction before and after the damage occurrence, on January 17 and July 31, respectively. The quantitative comparison of the dynamic displacement of the GPS observations with the integrated dynamic displacement of the accelerometer observations may not be realistic, since the static and quasi-static displacement components are missing from the accelerometer-derived displacement results (Li et al. 2006). Figure 6.a shows a good correlation between the dynamic displacement of both GPS and accelerometer observations in the X-direction, which represent bridge tower cables direction, in the undamaged monitoring case on January 17. This indicates that the tower dynamic vibrations depend totally on the cables forces and vibrations.

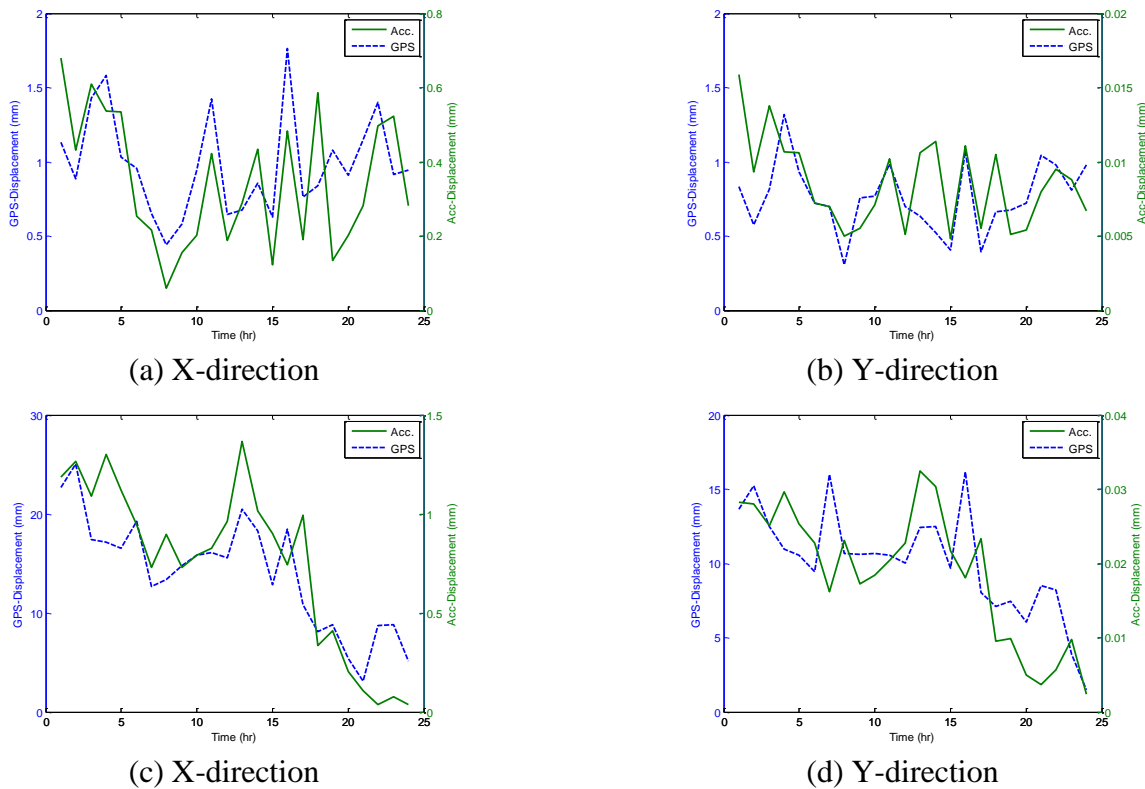


Figure 6 Maximum dynamic displacement component of GPS and accelerometer observations of the bridge tower in both horizontal directions; (a), (b) Before damage on January 17; (c),(d) After the damage occurrence on July 31

Whereas, Figure 6.b shows less correlation in the Y-direction, due to the lack of dynamic vibrations in this direction, which is affected only by the wind forces and the relative vehicle case of loading on the two-lanes of the main girder. Furthermore, after the damage and cracks occurrence, on July 31, Figure 6.c&d shows relatively low correlation in the maximum dynamic displacement of both GPS and accelerometer in the X- and Y-direction.

It also can be shown, due to the damage occurrence, that the dynamic displacements of GPS are increased by 10 to 15 times, whereas the dynamic displacements of the accelerometer observations are doubled in the X- and Y-direction, respectively, due to the damage occurrence. In addition, from Figure 6.c&d, after the damage occurrence on July 31, it can be seen that dynamic displacement for both GPS and accelerometer fall dramatically after the observation hour at 18:00, where after that hour, the traffic and vehicle passage was prevented to observe the bridge tower displacement due to this prevention. This indicates that the effective load on the bridge deck and tower dynamic displacements is the vehicle-moving load. Finally, it can be concluded that using the bridge tower integrated GPS/accelerometer observations can be useful to detect the bridge cracks and damage effects, mainly in the bridge cables direction.

### ***GPS/Accelerometer Fundamental Frequencies***

The fundamental frequencies of both the accelerometer observed acceleration and the calculated acceleration from the GPS displacement observations of the bridge tower in X- and Y-direction of 24-hour observations are shown in Figure 7. A double differentiation procedure is applied to the GPS measured displacement observations in both X- and Y- direction of all the 24-hour observations data in order to convert the displacement into acceleration time histories.

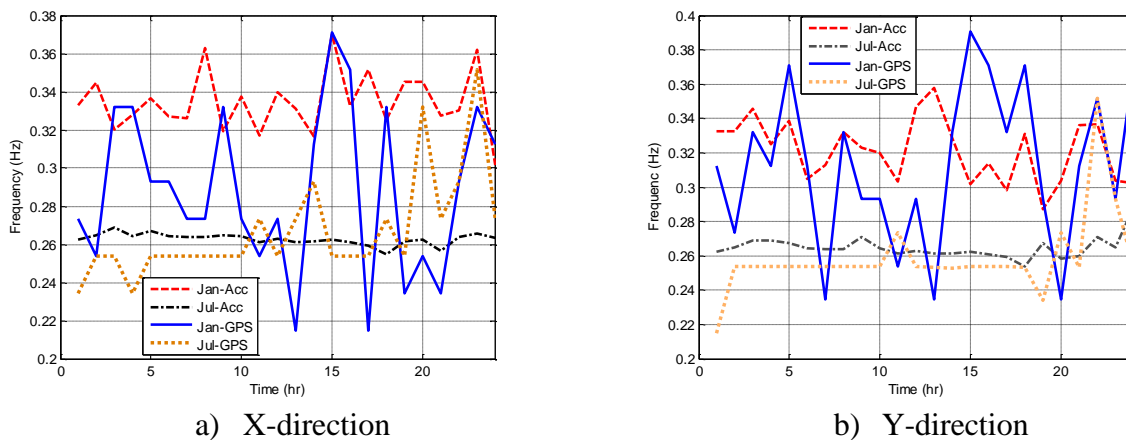


Figure 7 Fundamental frequencies of the GPS and accelerometer acceleration observations in X- and Y-direction before and after the damage occurrence

Furthermore, a band-pass filter was applied to this procedure to eliminate the GPS signal noises. From Figure 7.a, it can be shown in the X-direction of the 24-hour observations before the damage occurrence at January 17, that the fundamental frequencies range of the accelerometer observations is (0.32 - 0.37 Hz) while it is (0.21 - 0.37 Hz) for the GPS calculated acceleration observations. While, after the damage and cracks occurrence on July 31, the fundamental



frequencies range turns into (0.25 - 0.27 Hz) for the accelerometer observations, and (0.23 - 0.35 Hz) for the GPS calculated acceleration observations. Figure 7.b shows the fundamental frequencies of the accelerometer and GPS acceleration observations of 24-hour observations of the bridge tower in the Y-direction before and after damage occurrence. From Figure 7.b, it can be shown that, the fundamental frequencies range of the accelerometer observations changes from (0.28 - 0.35 Hz) to (0.25 - 0.28 Hz) due to damage effect. While, the fundamental frequencies range turns from (0.23 - 0.39 Hz) into (0.21 - 0.35 Hz) for the GPS calculated acceleration observations after the damage occurrence on July 31.

From previous results, it can be shown that the fundamental frequency calculations of both the accelerometer and GPS observations give close values to the fundamental frequency of the bridge FEM in both X- and Y-direction before the damage occurrence on January 17. In addition, the fundamental frequencies of the accelerometer during 24-hour acceleration observations of the bridge tower decreased by 24% and 15% in the X- and Y-direction, respectively, due to the damage effect on the bridge tower. However, the decrease of the fundamental frequencies of the GPS calculated acceleration observations are not significant in both horizontal directions. It means that both the GPS and accelerometer can detect the damage effect on the bridge tower separately, but the accelerometer is more sensitive in the damage detection in both horizontal direction of the bridge tower.

## **CONCLUSIONS**

The present study reports the damage and cracks detection of the cable-stayed Yonghe Bridge using the integrated GPS and accelerometer observations of the bridge southern tower. The tower movement analysis in both X- and Y-direction is discussed in both time and frequency domains under the ambient environmental loads (wind and temperature) and vehicle loads in the two monitoring cases: before and after the damage and cracks occurrence. The conclusions drawn from this study are as follows:

- The Moving Average and band-pass filters are suitable tools to extract the bridge tower quasi-static and dynamic displacement components from the GPS observations in both horizontal directions.
- Although the bridge damage was located mainly in the bridge deck, but the bridge tower suffers more displacements and vibrations after the damage occurrence due to the cables.
- The effective load that governs the bridge deck and tower dynamic displacements is the traffic load.
- The integrated GPS/accelerometer observations can be used to detect the bridge cracks and damage effects, mainly in the bridge cables direction.
- Both GPS and accelerometer observations can be used to detect the damage effect separately, however the accelerometer observations are more sensitive to detect the damage effect in both horizontal direction of the bridge tower.

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## REFERENCES

- Chang, P.C., Flatau, A. and Liu, S.C. (2003). "Review Paper: Health monitoring of civil infrastructure", *Structural Health Monitoring*, 2: 257.
- Elgamal, A., Conte, J.P., Fraser, M., Masri, S., Fountain, T., Gupta, A., Trivedi, M. and El Zarki, M. (2003). "Health monitoring for civil infrastructure", *Proceedings of the 9th Arab Structural Engineer Conference (9ASEC)*, Abu Dhabi, United Arab Emirates, November 29-December 1. Chipcon AS.
- Hwang, J., Yun, H., Park, S., Lee, D. and Hong, S. (2012). "Optimal methods of RTK-GPS/Accelerometer integration to monitor the displacement of structures", *Sensors J.*, 12, 1014-1034.
- Kalooop, M.R. and Li, H. (2009). "Monitoring of bridge deformation using GPS technique", *KSCE J. of Civil Engineering*, 13(6):423-431.
- Kalooop, M.R. and Li, H. (2011). "Sensitivity and analysis GPS signals based bridge damage using GPS observations and wavelet transform", *Measurement J.*, 44(5):927-937.
- Li, H., Li, S., Ou, J. and Li, H. (2010). "Modal identification of bridges under varying environmental conditions: Temperature and wind effects", *Struct. Control Health Monit.*, 17: 495-512.
- Li, H., Li, S., Ou, J. and Li, H. (2012). "Reliability assessment of cable-stayed bridges based on structural health monitoring techniques", *Structure and Infrastructure Engineering*, 8(9):829-845.
- Li, S., Li, H., Liu, Y., Lan, C., Zhou, W. and Ou, J. (2013). "SMC structural health monitoring benchmark problem using monitored data from an actual cable-stayed bridge", *Struct. Control Health Monit.*, doi:10.1002/stc.1559.
- Li, X., Ge, L., Ambikairajah, E., Rizos, C., Tamura, Y. and Yoshida, A. (2006). "Full-scale structural monitoring using an integrated GPS and accelerometer system", *GPS Solutions J.*, 10(4), 233-247.
- Meng, X., Dodson, A. and Roberts, G. (2007). "Detection bridge dynamics with GPS and triaxial accelerometers", *Engineering Structures J.*, 29, 3178-3184.
- Moschas, F. and Stiros, S. (2011). "Measurement of the dynamic displacements and of the modal frequencies of a short-span pedestrian bridge using GPS and an accelerometer", *Engineering Structures J.*, 33, 10-17.
- Moschas, F. and Stiros, S. (2013). "Noise characteristics of high-frequency, short-duration GPS records from analysis of identical, collocated instruments", *Measurement J.*, 46, 1488-1506.
- Roberts, G.W., Meng, X. and Dodson, A.H. (2004). "Integrating a global positioning system and accelerometers to monitor the deflection of bridges", *J. of Survey engineering*, ASCE, 130,2:65.
- Sohn, H., Farrar, C.R., Hemez, F.M., Shunk, D., Stinemates, D.W., Nadler, B.R. and Czarnecki, J. (2004). "A review of structural health monitoring literature: 1996-2001", *Los Alamos National Laboratory Report*, LA-13976-MS.