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Movement assessment of a cable-stayed bridge tower based on integrated GPS and accelerometer observations

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ABSTRACT

GPS and accelerometer sensors are used widely to observe the damage and to extract the movements of structures. Real time kinematic (RTK) dual-frequency GPS and dual-axis accelerometer are used in monitoring the movements of the cable-stayed Yonghe bridge tower under ambient environmental and vehicle loads. Integrated displacement, acceleration time histories of the GPS, and the accelerometer observations were extracted and compared in both time and frequency domains. 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 analysis show relatively high correlation of the GPS-accelerometer observations in the both time and frequency domains.

1. INTRODUCTION

Dynamic observation, analysis, identification and damage detection are considered one of the main aims of the structural health monitoring (SHM) of structures. Many types of sensors are used in SHM to monitor and observe the structural movements. Global positioning system (GPS) is considered one of the important sensors which are used to measure the static and quasi-static components of structures displacements (Moschas and Stiros 2011). In addition, accelerometer is also considered one of the sensors, which is used to measure the dynamic displacement of structures (Hwang et al. 2012). Many studies used and applied GPS or accelerometer sensors to monitor and asses the behavior of different types of structures separately; refer to (Kaloop and Li 2011; Li et al. 2013). Furthermore, some of previous studies applied and examined the integration of GPS and accelerometer measurements and observations; refer to (Chan et al. 2006; Meng et al. 2007; Hwang et al. 2012).

Preliminary studies have proven the technical feasibility of using GPS to monitor the dynamic structural deformation due to winds, traffic, earthquakes and similar loading events (Ashkenazi and Roberts 1997; Roberts et al. 2001). Moschas and Stiros (2013)

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concluded that the frequency range 0.4~5.0 Hz covers a wide variety of dynamic motions, including oscillations of most engineering structures and earthquake events. Such motions can reliably be described by the high frequency component of 10 Hz GPS. In addition, frequency range 0~0.4 Hz corresponds to semi-static displacement, for instance slow displacements induced by temperature changes, and the corresponding long-period component of displacements are to a smaller or larger degree contaminated by colored noise (Meng et al. 2007; Moschas and Stiros 2013). Furthermore, using the accelerometer sensors in monitoring structures enables to extract the acceleration response of structures with natural frequency up to 1000 Hz because of the high sampling frequency (Chan et al. 2006).

In this study the integration of GPS and accelerometer sensors observations are used to extract the full behavior of the cable-stayed Yonghe Bridge tower. Where, Fig.1 shows the elevation and SHM system components on the bridge. The Yonghe Bridge has two lanes with a main girder total width of 14.00 m and with total length of 510.00 m while the main span is 260.00 m as shown in Fig. 1. The bridge has two towers with total height of 60.50 m. This study is concerned in studying the behavior of the southern bridge tower, which is located in the Tianjin city side. The SHM system for the Yonghe Bridge comprises a data acquisition and processing system with a total of 179 sensors, including accelerometers (with range ±2 g and sensitivity of $5x10^{-5}$ g) and three GPS units. The GPS units were permanently installed on the two towers top points and in the river bank near the bridge. The GPS observations are real time kinematic (RTK) with differential GPS system. The receivers, which used are LEICA GMX902 antenna (20 HZ data rate, accuracy of 1mm+0.5ppm (horz.); 2mm+1ppm (ver.)) and observation data was pre-processed in the WGS84 coordinate system using the software GPS Spider 2.1. For more details about the bridge and SHM system used, refer to (Li et al. 2013). Finite element models (FEM) were widely carried out to assist the structure design. The FEM of the Yonghe Bridge was modeled based on the engineering drawings and the modal frequencies were used to support the GPS/accelerometer integration results.

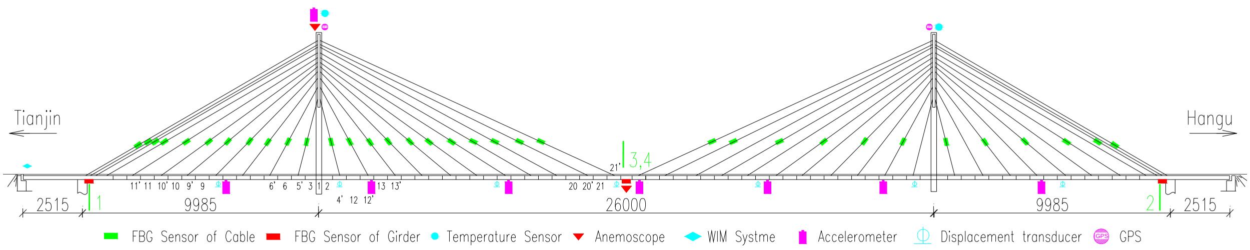


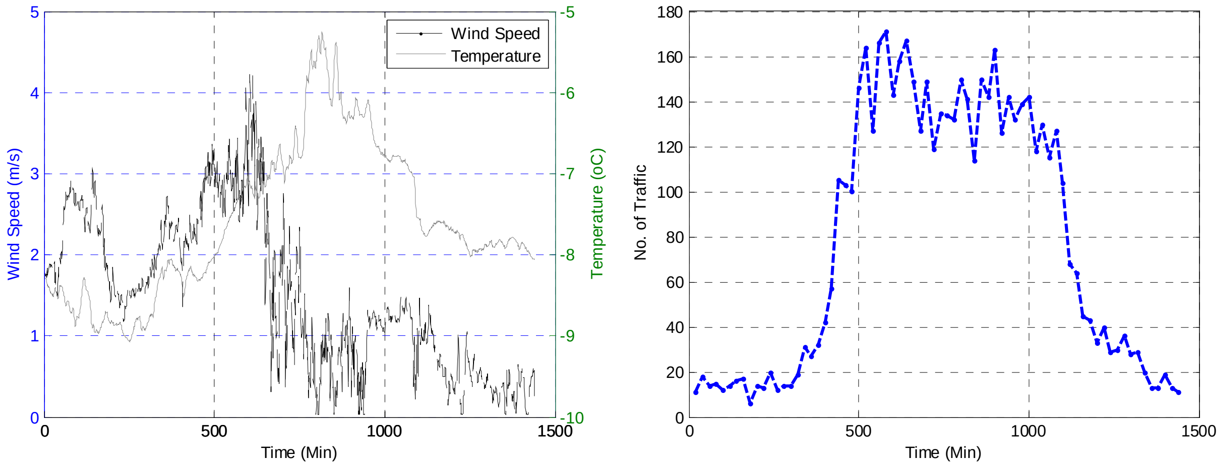
Fig.1 Elevation and SHM system of Yonghe Bridge

However, the aims of the study are:1)studying the bridge tower movement behavior under different loads; 2)using the FEM modal frequencies to support the integrated GPS/accelerometer comparisons; 3)examining the integration of GPS/accelerometer observations in both time and frequency domains. Finally, the integrated

GPS/accelerometer observations of the bridge tower are analyzed and discussed.

2. BRIDGE TOWER MOVEMENT ANALYSIS

The Yonghe Bridge southern tower movement analysis in both X- and Y-direction is presented in this paper. The data collected from SHM on January 17, 2008 was used in this section to analyze the tower movements and sensors integrations. The integration of GPS/accelerometer sensors in both time and frequency domains is presented in this study. 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. Fig. 2.a shows the average temperature and wind speed in the observing day, while Fig. 2.b shows the number of vehicle traffic passing on bridge lanes in the same day. From both Figures, it can be seen that the maximum wind speed is about 4 m/sec^2, the average temperature difference is about 3.8 ^{o}C and the maximum number of vehicles passing is 171.



(a) Temperature and wind speed (b) Number of traffic

Fig. 2 Environmental loads and no. of vehicles on January 17, 2008

2.1 Yonghe Bridge Modeling

A three-dimensional FEM of the Yonghe Bridge was modeled on the basis of 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 510.00m 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 with variable cross sectional area from 78.14 cm^2 to 27.10 cm^2, referred to the bridge structural drawings. The ambient environmental loads (wind speed and temperature degrees) and the vehicle moving loads from Fig. 2 are considered in the bridge model. In addition, additional secondary uniform dead load of 1.90 t/m^2 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. Moreover, the longitudinal restriction effect of the rubber support is simulated using linear elastic spring elements. The bridge FEM first mode shape is shown in Fig. 3. In addition, the first five modal frequencies of the bridge are 0.3033 Hz, 0.4063 Hz, 0.6158 Hz, 0.7966 Hz and 0.8151 Hz, respectively.

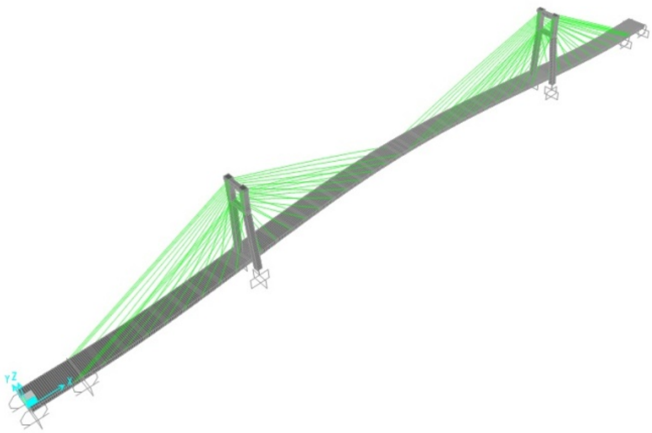


Fig. 3 Yonghe Bridge finite element first mode shape

2.2 Bridge Tower GPS/Accelerometer Data Integration

2.2.1 Displacement time series analysis:

Due to complex noises in the GPS data, and to analyze and identify the signals, a pre-processing procedure should be done first (Yu et al. 2006). The pre-processing should be used to delete the noises and to extract the useful signals. Moving average (MA) filter was used widely to eliminate time history GPS noises (Meng 2002; Moschas and Stiros 2011; 2013). The time series of X- and Y- direction displacement observations h_i around a relative zero representing the equilibrium level of the monitoring point. This similarity transformation was based on Eq. (1).

$$h_i = d_i - {}^{1}/_{n} \sum d_i \tag{1}$$

where; i=1,2,3,…n, n represents the total number of observations interval before, while d represents the X- and Y-direction observations values.

Fig. 4.a shows one-hour of the tower displacements of the GPS observations in the Y-direction. From this Fig., it can be seen that some errors and noises are shown along

the displacement data. Therefore, a MA filter is used to smooth the displacement observations as shown in Fig. 4.a. It can also be shown that using MA filter is a good tool to detect the long-period component of the bridge tower GPS displacement with no loss in information for the displacement data and with high correlation.

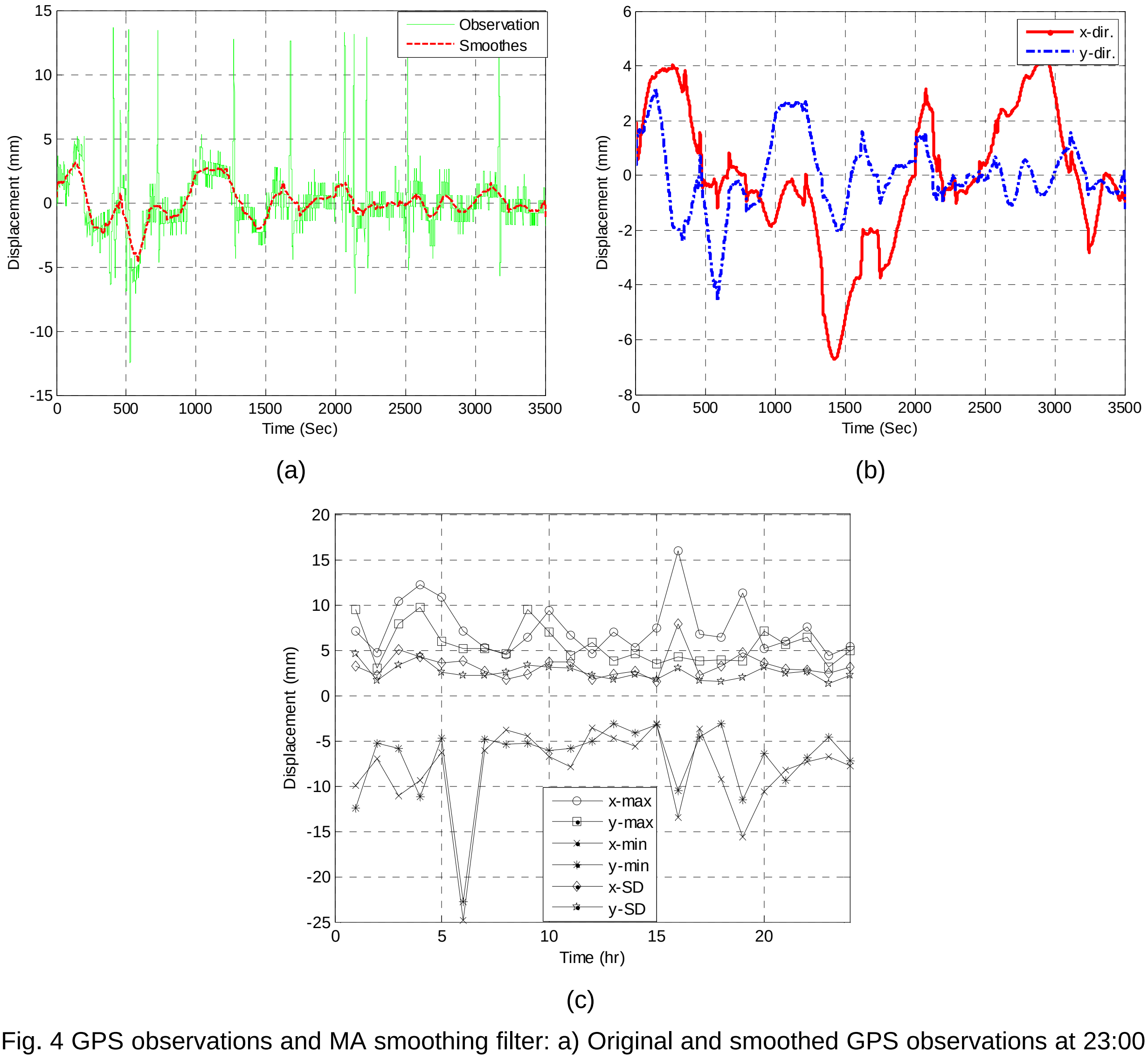
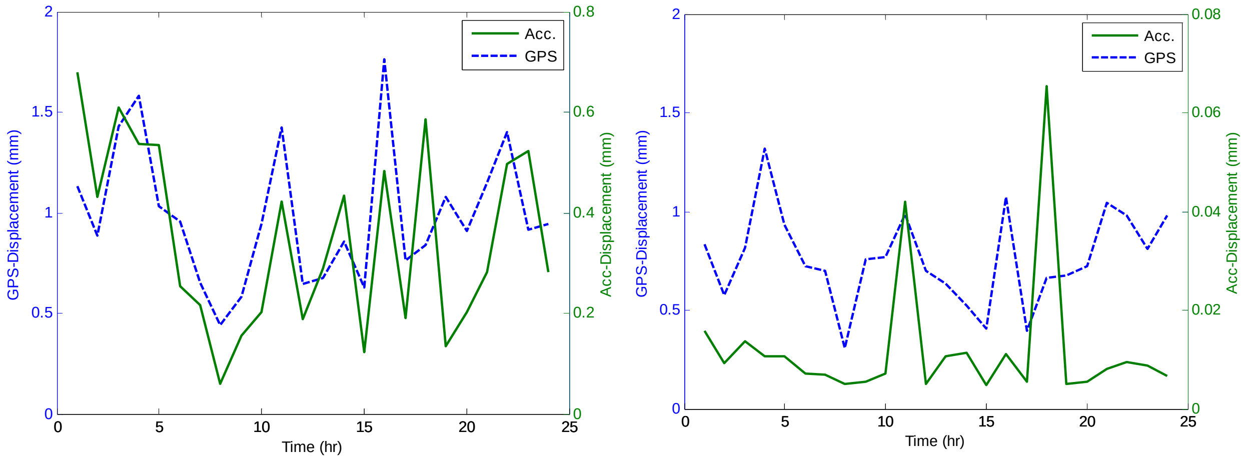


Fig. 4 GPS observations and MA smoothing filter: a) Original and smoothed GPS observations at 23:00 ; b) GPS smoothed observation of X- and Y-directions at 23:00; c) GPS displacement statistics during the observing day on January 17, 2008

Fig. 4.b shows the smoothed displacements in both X- and Y-direction of the tower while Fig. 4.c shows the GPS displacement statistics of a complete day observations on January 17, 2008. From Fig. 4.c, it can be seen that the tower displacements in the X- and Y-direction show peak values from 11:00 to 16:00 and from 23:00 to 24:00. In

addition, the maximum mean displacement becomes significant at 1:00 and equals to 0.053 mm, 0.042 mm, in X- and Y-direction, respectively, whereas, the minimum mean displacements are -0.029 mm and -0.017 mm in X and Y-direction, respectively. Accordingly, it can be shown that the tower displacement in two directions change in a similar manner. However, it can also be concluded that, the correlation between the two directions is strongly influenced. The maximum, minimum and standard deviation (SD) for the complete day smoothed data show that; the maximum displacement values are 16.00 mm at 16:00 and 9.76 mm at 4:00. Furthermore, the minimum displacement values are -24.77 mm and -22.74 mm at 6:00 while the SD values are 7.94 mm at 16:00 and 4.64 mm at 1:00 in X- and Y-direction, respectively. These results indicate that the external loads on the bridge have a contribution on the displacement observations at times 1:00, 4:00, 6:00 and 16:00 for the observing data collected on January 17, 2008.

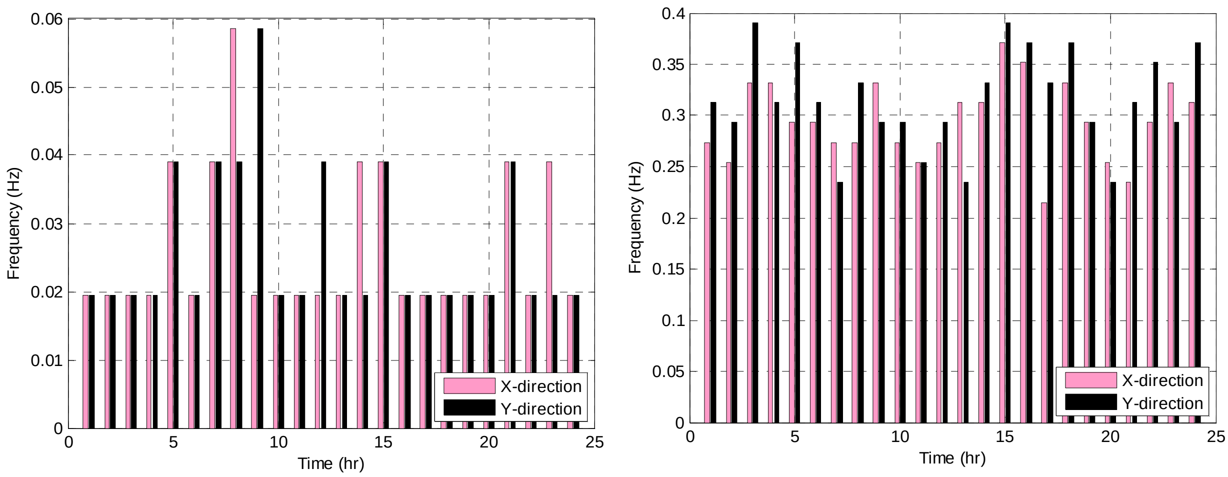


(a) X-direction (b) Y-direction

Fig. 5 Dynamic displacements components of GPS and accelerometer in the X-and Y-direction

The statistical calculations of the short-period component GPS and accelerometer dynamic displacements show that the correlation coefficients are 0.63 and 0.11 in the X- and Y-direction, respectively. The relatively high correlation coefficient in the X-direction proves that in this direction and due to cable forces and dynamic vibrations, both short-period component GPS and accelerometer dynamic displacements are correlated and the obvious reason that reduces this correlation is the noises in the GPS short-period displacement components. In the opposite, the low correlation coefficient in the y-direction due to the lack of the loads and the dynamic vibrations in this direction and due to the high GPS signals noises in this direction

Fig. 5 shows the maximum dynamic displacements comparison between the accelerometer and GPS sensors observations in both X- and Y-direction. Where, the dynamic displacement of the accelerometer is derived from the double integration of the acceleration time histories observations recorded by the accelerometer sensor using band bass filter to eliminate the high frequency noises of the observations. While the dynamic displacement of the GPS observations represent the short-period component of the GPS displacements. Where, the short-period component of the GPS displacements can be extracted from the GPS displacement time histories after subtracting the long-period displacement component from the GPS displacement data, and the short-period component consists of dynamic displacement and remnant noise. The dynamic vibrations (dynamic component of the GPS and accelerometer displacements) can be related to each other, but it is hard to compare quantitatively the dynamic displacement of the accelerometer with the dynamic component of the GPS observations because the static and quasi-static displacements are missing from the accelerometer-derived results (Li et al. 2006). Fig. 5.a shows a good correlation between the dynamic component of the GPS and accelerometer displacements in the X-direction, which represent bridge tower cables direction. This indicates that the tower dynamic vibrations depend totally on the cables forces and vibrations. Fig. 5.b shows less correlation between the accelerometer and GPS dynamic displacement components in the Y-direction. This is because of the lack of dynamic vibrations in this direction, which is affected only by the wind and the relative vehicle case of loading on the two-lanes of the main girder.

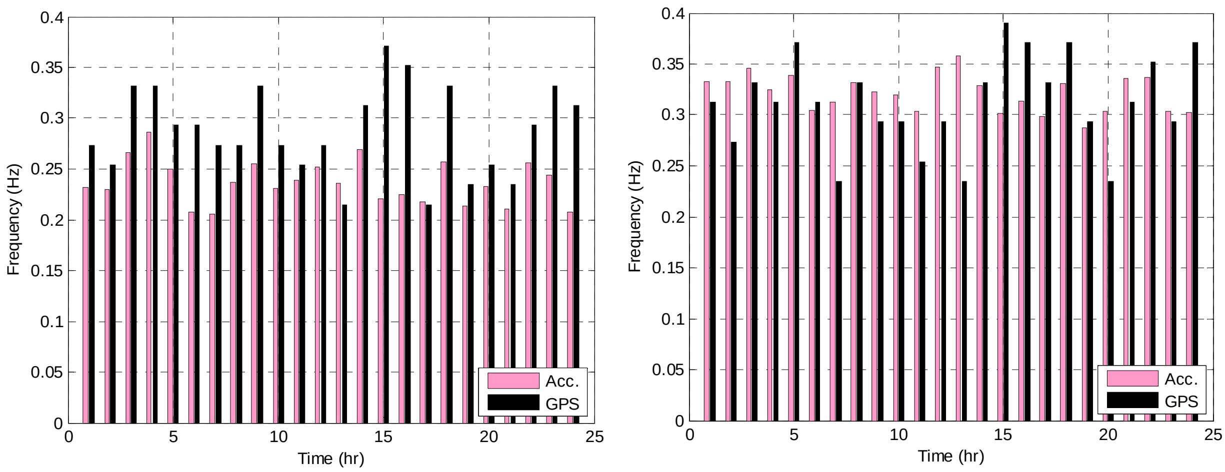


(a) Low frequency component (b) High frequency component

Fig. 6 Fundamental frequency components of the GPS displacement observations in the X- and Y-direction

2.2.2 Tower movements frequency analysis:

The transformation of the time series observations from the time domain to the frequency domain was performed by applying the Fast Fourier Transform (FFT). In addition, the power spectrums for the low and high frequencies components of the time series were calculated. Fig. 6 shows the fundamental frequency components of the GPS displacement observations in both X- and Y-direction for all the 24-hour observations data. Both low and high pass filters were used based on the fundamental frequency extracted from the FEM of the bridge. From this Fig., it can be seen that the low frequency component of the GPS displacement observations do not suffer changes along most of the observations hours and equals to 0.0195 Hz in both X- and Y-direction. In addition, it can also be shown that the peak value of the high frequency component of the GPS displacement observations happen to occur at 15:00 and equals to 0.37 Hz and 0.39 Hz for the X- and Y-direction, respectively. It also can be seen that the high frequency components ranges of the GPS displacement observation during the 24 observations data were convergent and close to the fundamental frequency of the bridge FEM. From these results, it can be concluded that the changing of the loads over the day representing in number of vehicle passing over the bridge and variable ambient environmental loads (wind and temperature) during the day affect the bridge tower movements, which is obvious due to the changing in the fundamental frequency of every observation hour data. In addition, it is also been found that the low and high frequencies obtained from the power spectrums of the GPS displacement observations reflected the expected movements of the bridge tower. Furthermore, the high frequency components of the GPS displacement observations can be a useful tool to extract the modal frequencies of structures.



(a) X-direction (b) Y-direction

Fig. 7 Fundamental frequencies of the GPS and accelerometer acceleration observations in X- and Y-direction

The fundamental frequencies in the frequency domain of the acceleration observations of the accelerometer and the calculated acceleration from the GPS displacement observations in X- and Y-direction of 24-hour observations are shown in Fig. 7. A double differentiation procedure applied to the GPS measured displacement data in both X- and Y- direction of all the 24-hour observations data in order to convert the displacement into acceleration time histories. Furthermore, a band pass filter was applied in this double differentiation procedure to eliminate the GPS signal noises. In addition, the acceleration time histories measured by the accelerometer in both X- and Y-direction are filtered to eliminate the high frequency noise. Form Fig. 7.a, it can be shown in the X-direction of the 24-hour observations, that the fundamental frequencies range of the accelerometer observations is (0.20 ~ 0.28 Hz) while it is (0.21 ~ 0.37 Hz) for the GPS calculated acceleration observations. Form Fig. 7.b, it can be shown, that the fundamental frequencies range of the accelerometer observations is (0.28 ~ 0.35 Hz) while it is (0.23 ~ 0.39 Hz) for the GPS calculated acceleration observations in the Y-direction of the 24-hour observations.

The statistical calculations of the fundamental frequencies in the frequency domain of the acceleration observations of the accelerometer and the calculated acceleration from the GPS displacement observations in X- and Y-direction of the 24-hour observations were done to extract the mean and the standard deviation (SD) as shown in table 1. From table 1, it can be shown for both X- and Y-direction that the mean and standard deviation of the acceleration fundamental frequencies of the 24-hour observations for accelerometer and GPS are convergent values. From the results it can be shown that the fundamental frequency calculations of GPS observations give close values to the fundamental frequency of the FEM in both X- and Y-direction. It means that the GPS frequency analysis can extract the dynamic behavior of the bridge tower movement analysis under ambient environmental and vehicle loads.

Table 1 Mean and standard deviation of fundamental frequencies of the GPS and accelerometer acceleration in X- and Y-direction

	X-direction		Y-direction	
	Acc.	GPS	Acc.	GPS
Mean	0.23 Hz	0.28 Hz	0.32 Hz	0.31 Hz
SD	0.02 Hz	0.04 Hz	0.01 Hz	0.04 Hz

3. CONCLUSIONS

The present study reports the integration of GPS and accelerometer observations of the Yonghe Bridge southern tower movement analysis. The tower movement analysis in both X- and Y-direction are discussed in both time and frequency domains under the ambient environmental loads (wind and temperature) and vehicle loads. The conclusions drawn from this study are as follows:

- The moving average filter is considered a good tool to detect the long-period component of the GPS displacement with no loss in information and with high correlation.
- The short-period displacement components of the GPS and the accelerometer displacements in bridge cable directions show a relatively high correlation due to the dynamic vibration in this direction. In contrast, in Y- direction they show less correlation due to the lack of the dynamic vibration and due to the high GPS signal noises in this direction.
- Loads change throughout the day affect the bridge tower movements and cause

changing in the fundamental frequency of the observation through the day.

- The low and high frequencies obtained from the power spectrums of the GPS displacement observations reflects the expected movements of the bridge tower. In addition, the high frequency components of the GPS displacement observations can be a useful tool to extract the fundamental frequencies of structures.
- GPS/accelerometer observations integration show relatively high correlation in both time and frequency domains in the bridge cables direction due to the dynamic vibration in this direction.

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