Smart Structures and Systems, *Vol. 25, No. 1 (2020) 111-122*
DOI: https://doi.org/10.12989/sss.2020.25.1.111

Combining GPS and accelerometers' records to capture torsional response of cylindrical tower

Raed J. AlSaleh*[1] and Clemente Fuggini[2]

[1] *Department of Civil and Environmental Engineering – German Jordanian University, Jordan*
[2] *Research and Innovation – RINA, Italy*

(*Received April. 13, 2019, Revised August 22, 2019, Accepted November 12, 2019*)

Abstract. Researchers up to date have introduced several Structural Health Monitoring (SHM) techniques with varying advantages and drawbacks for each. Satellite positioning systems (GPS, GLONASS and GALILEO) based techniques proved to be promising, especially for high natural period structures. Particularly, the GPS has proved sufficient performance and reasonable accuracy in tracking real time dynamic displacements of flexible structures independent of atmospheric conditions, temperature variations and visibility of the monitored object. Tall structures are particularly sensitive to oscillations produced by different sources of dynamic actions; such as typhoons. Wind forces induce in the structure both longitudinal and perpendicular displacements with respect to the wind direction, resulting in torsional effects, which are usually more complex to be detected. To efficiently track the horizontal rotations of the in-plane sections of such flexible structures, two main issues have to be considered: a suitable sensor topology (i.e., location, installation, and combination of sensors), and the methodology used to process the data recorded by sensors. This paper reports the contributions of the measurements recorded from dual frequency GPS receivers and uni-axial accelerometers in a full-scale experimental campaign. The Canton tower in Guangzhou-China is the case study of this research, which is instrumented with a long-term structural health monitoring system deploying both accelerometers and GPS receivers. The elaboration of combining the obtained rather long records provided by these two types of sensors in detecting the torsional behavior of the tower under ambient vibration condition and during strong wind events is discussed in this paper. Results confirmed the reliability of GPS receivers in obtaining the dynamic characteristics of the system, and its ability to capture the torsional response of the tower when used alone or when they are combined with accelerometers integrated data.

Keywords: structural health monitoring; torsional response; typhoons; GPS; accelerometers; long period structure

1. Introduction

In any Structural Health Monitoring (SHM) scheme applied to a civil structure, accuracy, durability and availability are requirements that must be strictly satisfied in order to guarantee feasible and reliable long-term application. Various types of sensors are available now to achieve this purpose, among them accelerometers have played the most important role in detecting structural response due to different loading conditions. However, data accelerometers provide relative acceleration measurements, and the displacement from acceleration measurement cannot be obtained directly by double integration.

On contrast. GPS receivers can measure the position coordinates of an object at each instance, hence the displacement time history of a structure can be directly obtained, from which the dynamic characteristics of the structure could be easily identified.

The use of GPS provides response signals sampled at sufficiently high frequency, which is proved able to detect the dynamic behavior of structures of long periods in terms of displacements variations (Kaloop 2017, Casciati and Fuggini 2011, Kim *et al*. 20016, Kijewsji-Correa *et al*. 2006). This led these receivers to be utilized in the full-scale monitoring system of tall building structures (Gorski 2017, Kijewsji-Correa and Kochly 2007, Gorski and Konopka 2009, Li *et al*. 2007) as well as bridge structures (Peppa *et al*. 2018, Elbeltagi *et al*. 2014, Moschas *et al*. 2013, Yi *et al*. 2013, Kaloop 2012). Moreover, the use of GPS receivers recently has extended to outlier detection of abnormal events to protect structures from sudden failure during their service lives (Yi *et al*. 2017).

Nevertheless, the need for accelerometers data did not vanish because GPS also has some limitations. For example, the accuracy of the obtained measurements can be affected by multipath and it depends strongly on satellite geometry. Therefore, the use of combined system for SHM, which consists of GPS receivers deployed along with accelerometers, has been proven to be efficient (Hwang *et al*. 2012, and Kuang *et a*l. 2011). In this case, it is either required to convert GPS measured displacement to acceleration through double differentiation in order to compare it with the accelerometer measurements, or to convert the accelerations into displacements through double integration to compare them with GPS displacements. The double integration process is quiet challenging because two integration constants have to be determined in order to recover the static and quasi-static components, especially

*Corresponding author, Ph.D.,
E-mail: raed.alsaleh@gju.edu.jo

http://www.techno-press.org/?journal=sss&subpage=7
ISSN: 1738-1584 (Print), 1738-1991 (Online)

when the monitored structure is affected by extreme wind events like typhoon (Li *et al*. 2005). In fact, it has been found that GPS and accelerometers can be used to supplement each other, providing more efficient SHM (Psimoulis *et al*. 2015). As a result, processing of GPS data has interested many researchers in the literature to reach for the most appropriate procedures that lead to optimum system identification, and dynamic parameters' definition of a structure (Pehlivan 2018, Yi *et al*. 2017).

In tall building, the dynamic forces that produce oscillation of the structure are generated mainly from winds. Wind forces induce displacement responses in the structure in its both longitudinal and transversal directions, consequently, such two directional in-plane forces combine into torsional responses; which are mostly more complex to be detected during full-scale experimental tests. Previous arrangement of sensors topology (i.e., sensors combinations and locations) is quite important; they should be distributed sufficiently on an upper level of the structure to provide measurements from which torsion could be calculated.

This led GPS receivers to be utilized in the full-scale monitoring system of structures like Canton tower in Guangzhou-China. (Formerly called Guangzhou New TV Tower) (Ni *et al*. 2008, and Ni and Zhou 2010) which is the test bed of this paper. A network of GPS receivers, installed on the top of Canton tower and other types of sensors were presented in the literature (Ni *et al*. 2008). The data obtained from these sensors were made available to the authors in order to examine the feasibility of a structural health monitoring GPS network and its ability to provide reliable accuracy in detecting the induced torsional effects on the tower. In fact, such structures as tall buildings are most likely to experience oscillations produced mainly by strong wind events (Li *et al*. 2007).

In general, this study is reporting displacement measurements acquired by GPS receivers that are analyzed and processed aiming at proving their ability in detecting the response (i.e., in-plane displacements and in-plane rotations) of flexible structures of long period under ambient vibration. These data are then optimized to account for the influence of the geometrical configuration of satellites overhead before applying a simple mathematical procedure to calculate the variation of torsional parameter of the structure with time.

Furthermore, the movements of the tower during strong wind events were acquired by means of both GPS and accelerometer sensors deployed on the top level of the building, thus; the torsional response of the tower is detected from combining data from these two different sensors. The adopted procedure to process the displacement data, as recorded and elaborated from the acquired signals; aiming at detecting the torsional parameters of the tall building under ambient vibration conditions and extreme events is reported within this contribution.

2. Experimental configuration of Canton tower

The Canton tower was constructed in Guangzhou city in China in 2011; it has a total height of 610 m (Fig. 1). The tower is a tube-in-tube structure, comprising a reinforced concrete inner tube and a steel outer tube constructed adopting Concrete-Filled-Tube (CFT) columns style.

Fig. 1 Canton Tower in Guangzhou-China

The outer tube of the tower consists of 24 CFT columns, uniformly spaced in an oval, while inclined in the vertical direction. The oval section dimensions decrease with the altitude from (50 m × 80 m) at ground level to the minimum dimensions of (20.65 m × 27.5 m) at 280 m height, then they increase again to (41 m × 55 m) at the top level of the tube (454 m height). Steel ring beams and bracings interconnect the columns transversely. The inner tube has an oval shape as well, but with constant dimensions of (14 m × 17 m). Fig. 2 shows how the outer tube steel section of the tower changes with altitude in both dimensions and orientation (Ni *et al*. 2009a).

A SHM system consisting of over 600 sensors has been designed and implemented to monitor this tower by the Hong Kong Polytechnic University in Hong Kong, for both in-construction and in-service stages. For this purpose a SHM benchmark problem was conceived (Xia *et al*. 2008) considering Canton tower as a test structure and providing real time measurements for the structure's dynamic response. Within this context, collaboration with the Department of Civil Engineering at the Hong Kong Polytechnic University allowed the authors to get the data recorded by accelerometers and GPS mounted on the tower, and to interact in the GPS sensors placement process.

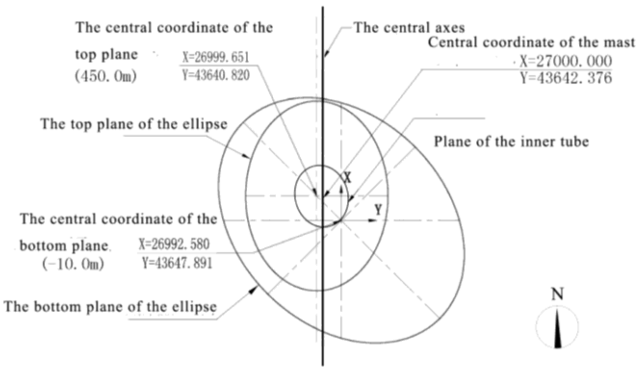


Fig. 2 Geometrical representation of the oval shape varied dimensions and orientation

Utilizing the directly recorded data from the tower response, attention is focused on the identification of preferable topology able to provide information on the torsional response of the structure when exposed to strong wind events, as typhoons, which occur frequently in the considered geographic area (AlSaleh *et al*. 2009).

3. Processing of available dynamic response data

Acquired data were obtained considering the need to study the torsional behavior of the tower under different conditions; therefore, two main scenarios are analyzed: firstly, by processing data recorded under ambient vibration condition by accelerometers aiming at detecting the torsional behavior to validate the results under similar condition when torsion is detected by data obtained by GPS receivers. The second is processing data recorded under two events of strong wind affected the tower, namely; the Nuri typhoon event occurred in August 2008 and the Hagupit typhoon event occurred in September 2008 in order to capture the torsional response of the tower when exposed to typhoons by combining data from accelerometers and GPS receivers.

The obtained data and how are they processed to achieve the target of detecting torsional behavior of the tower are explained in the following subsections in chronological order.

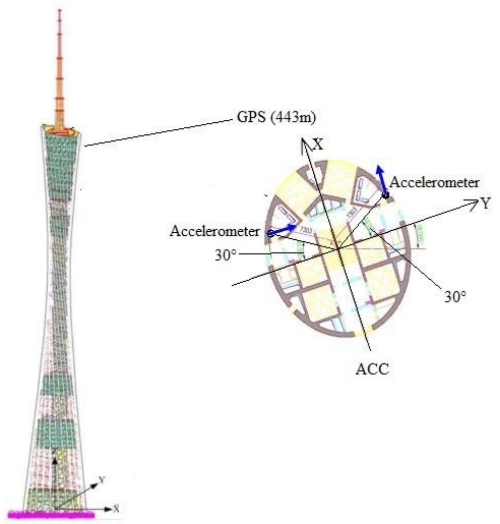


Fig. 3 Location of the measurement points during Nuri Typhoon

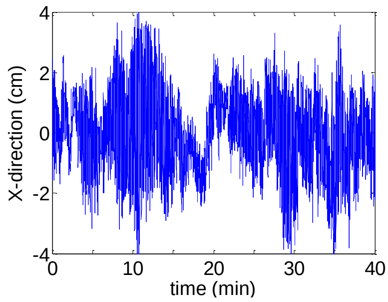
3.1 Data recorded during strong wind event

3.1.1 Nuri typhoon

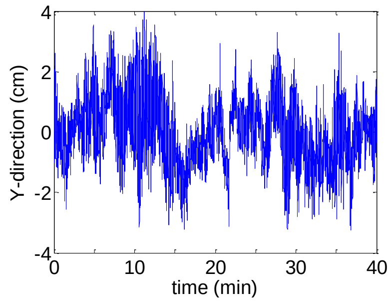
Nuri typhoon occurred, on August 22, 2008. On that day, two GPS receivers and two uni-axial accelerometers recorded data on site, they were positioned at the top level of the tower as shown in Fig. 3. One GPS receiver was placed in the center of the oval concrete inner tube cross section, while the other was fixed on the ground level so the differential global positioning system mode (DGPS) is applied. The two accelerometers were placed at the edges of this section, one along the East-West direction and the second along the North-South direction. The top level at this stage was at 443 m height.

The data set recorded during Nuri typhoon will be referred as: #Nur08, hereafter.

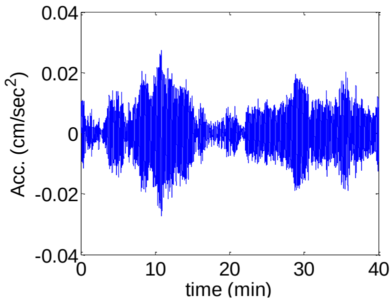
It is assumed -as denoted in Fig. 3- that the X-direction measurements obtained from the accelerometers correspond to the North coordinates of the GPS inner tube measuring point; while measurements in the Y-direction correspond to the East coordinates.



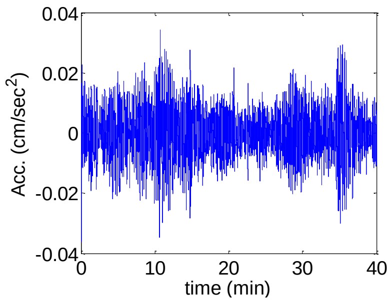
(a) Measured displacement in X-direction



(b) Measured displacement in Y-direction

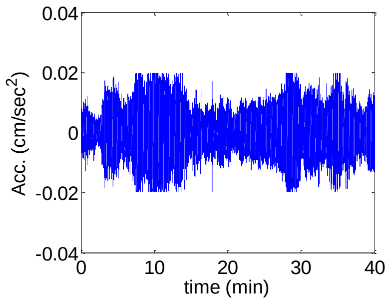


(c) Derived acceleration in X-direction

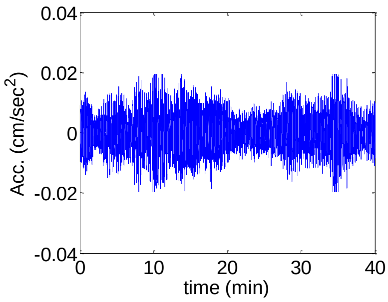


(d) Derived acceleration in Y-direction

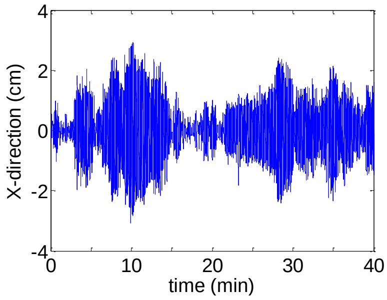
Fig. 4 Time histories from GPS records of #Nur08



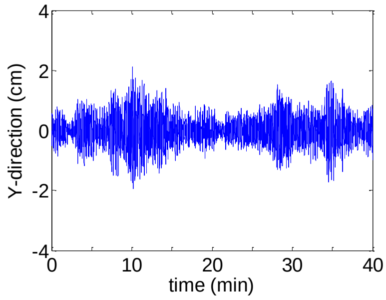
(a) Measured acceleration in X-direction



(b) Measured acceleration in Y-direction

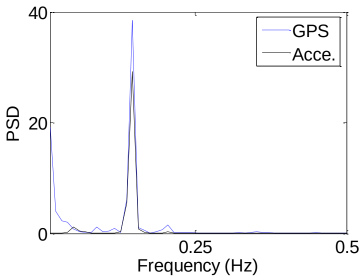


(c) Integrated displacement in X-direction

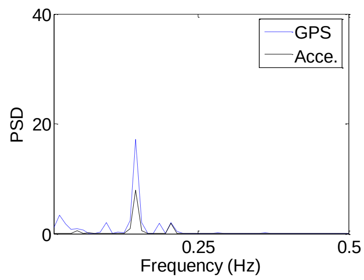


(d) Integrated displacment in Y-direction

Fig. 5 Time histories from accelerometer records of #Nur08



(a) PSD of displacement time histories in X-direction



(b) PSD of displacement time histories in Y-direction

Fig. 6 PSD of displacement time histories of #Nur08

The GPS data of #Nur08 was recorded from 2:00 to 5:00 p.m. A segment of 40 minutes duration is extracted from this data, and from those obtained by the accelerometers, referring to the time interval from 2:10 and 2:50 p.m. The maximum wind speed during the typhoon was 25.5m/s, measured by the aid of an anemometer placed on the top of the structure, and the wind direction was mostly Northeastern (Ni *et al*. 2009b). The GPS sampling rate was 5 Hz, while the sampling rate of the accelerometers was 50 Hz.

The displacement time histories in X and Y directions obtained from GPS receiver are drawn in Figs. 4(a) and (b) respectively, while Figs. 5(a) and (b) show the acceleration time histories obtained by the accelerometers. In order to combine these two types of data it is required either to integrate twice the acceleration records to get displacements that can be combined with GPS measurements, or to differentiate displacement twice to get acceleration that can be combined with accelerometers records.

The differentiation process is a simple process; it started with removing the mean from the displacement signals, and then the signals are resampled to match the accelerometers' records (50 Hz). After that, double differentiation is applied and a band-pass filter to extract noise associated frequencies. The resulted acceleration time histories are shown in Figs. 4(a) and (b).

The integration process is known to be more challenging than the differentiation, nevertheless, both operation are done for #Nur08 data. Integration process started with the raw signals shown in Figs. 5(a) and (b) after the signals' mean is removed, they are then subjected to a band-pass filter to extract the high frequencies related to noise. The signals are then double integrated assuming zero values of the integration constants, the resulted signals will have linear trends associated with the integration constant that might have a non-zero value. This trend can be then removed from the signal and the resulted displacement time histories are shown in Figs. 5(c) and (d).

Recalling the aim of this manuscript that is to capture the torsional response of the tower, combing the displacement records would give better expressions to represent torsion (i.e., twist and rotation angle) than

(a) Measured displacement in X-direction (b) Measured displacement in Y-direction

Fig. 7 Time histories from GPS records of #Hag08

(a) Integrated displacement in X-direction (b) Integrated displacement in Y-direction

Fig. 8 Time histories from accelerometer records of #Hag08

(a) PSD of displacement time histories in X-direction (b) PSD of displacement time histories in Y-direction

Fig. 9 PSD of displacement time histories of #Hag08

acceleration records. Therefore, in order realize the aim of this work, for #Nur08 data and the other data in the next subsection, displacements from GPS are combined with displacements obtained by double integration of accelerometers'' records, giving the fact that GPS displacements and integrated-acceleration displacements have reasonable conformity.

The Power Spectral Density (PSD) of GPS records against accelerometers records is plotted in Fig. 6 for both directions. All PSDs have a clear common amplitude at 0.146 Hz. This value corresponds to the natural frequency of the first mode of vibration at that stage of construction as was reported in AlSaleh 2011, which proves the capability of GPS receivers in dynamic analysis.

3.1.2 Hagupit typhoon

Another extreme wind event affected the tower on September 20, 2008, when Hagupit typhoon occurred. Response data were recorded, systematically, during Hagupit typhoon by the same set of sensors (i.e., accelerometers and GPS); which had the same locations on the inner tube of #Nur08 data, however, the height of the tower at this construction stage was 5 m higher (i.e., 448 m height). This data set will be referred as #Hag08, hereafter

The GPS data of #Hag08 was recorded from 1:00 to 5:00 p.m. A segment of 40 minutes duration is extracted from the entire obtained data, precisely; from 1:10 to 1:50 p.m. The displacement time histories of #Hag08 in X and Y directions obtained from GPS receivers are drawn in Fig. 7, while Fig. 8 shows the displacement time histories integrated twice from the acceleration records obtained by the accelerometers in X and Y directions. Systemically, the PSD of GPS records against accelerometers records is plotted in Fig. 9 for both directions. In this case, the PSDs have clear two common amplitudes; namely at 0.136 and 0.195 Hz. These frequencies are proven to be corresponding to those of the first and second modes of vibration of the tower at the stage of construction when Hagupit typhoon occurred (AlSaleh 2011). This confirms the conclusion of previous data.

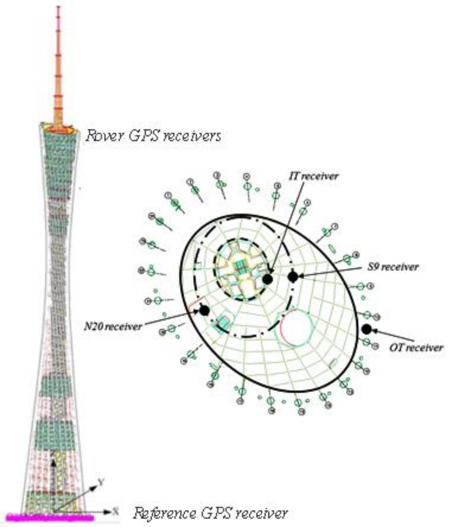
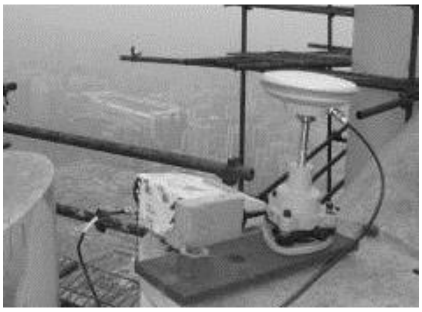


Fig. 10 Location of the measurement points for GPS sensors

3.2 Data recorded in the absence of significant wind event

On March 19, 2009 three GPS rover receivers (namely; N20, S9, IT receivers) were placed at the top achieved level of the tower at that time (450 m height), in addition to the reference receiver (namely; OT receiver) on the ground level, as shown in Fig. 10 and depicted in Fig. 11. Each GPS receiver on the top level was associated with an accelerometer located at the same position.

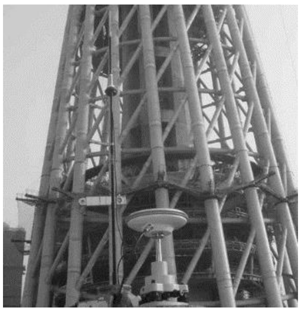
The tower did not suffer high excitation during the whole period in which these three GPS receivers were installed since no strong wind events happened. Nevertheless, the GPS obtained data were considered significant even if the tower was undergoing small oscillations produced by ambient vibrations (Faravelli *et al*. 2009, and Casciati *et al*. 2009). These data (referred as #Mar09) allowed getting information on a pseudo-initial configuration that considered as reference configuration of tower response.



(a) N20 receiver

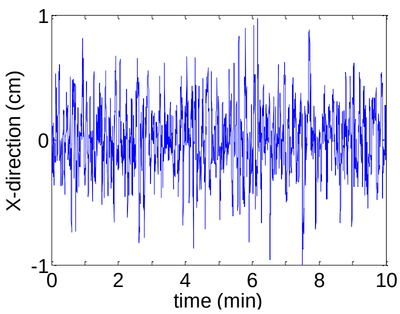
(b) S9 receiver

(c) IT receiver

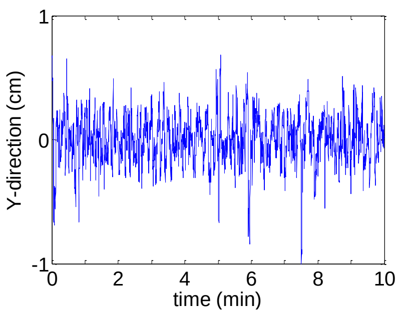


(d) OT receiver

Fig. 11 GPS receiver's placement on the top level (IT, N20, and S9), and ground level (OT)

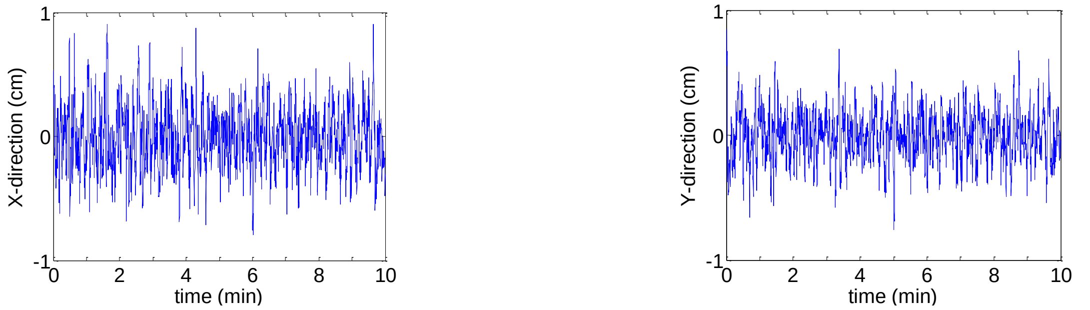


(a) Displacement time history in X-direction



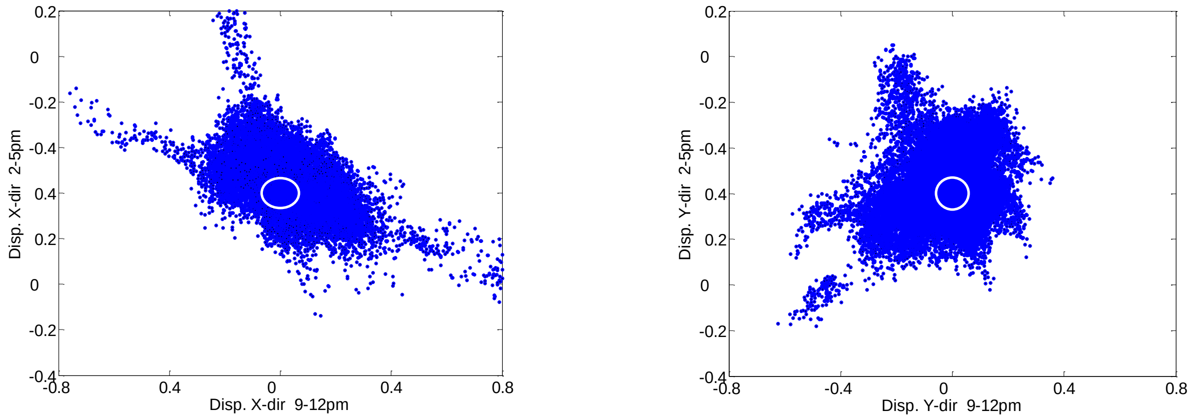
(b) Displacement time history in Y-direction

Fig. 12 GPS displacement time histories recorded by sensor N20



(a) Displacement time history in X-direction (b) Displacement time history in Y-direction

Fig. 13 GPS displacement time histories by S9



(a) Displacement data in X-direction (North) (b) Displacement data in Y-direction (East)

Fig. 14 Comparison of GPS data obtained during two different time intervals

The three receivers recorded the coordinate's variation of the points where they were located at a sampling rate of 5 Hz. It is assumed that the North GPS coordinates correspond to the X-direction measurements, while the East GPS coordinates to the Y-direction; which is the same correspondence adopted for accelerometers records of #Nur08 and #Hag08. A segment of 10 minutes is taken from the available data recorded by each of N20 and S9 GPS units (namely; from 9.00 to 9.10 a.m.). The displacements time histories are drawn in Figs. 12 and 13 from N20 and S9, respectively.

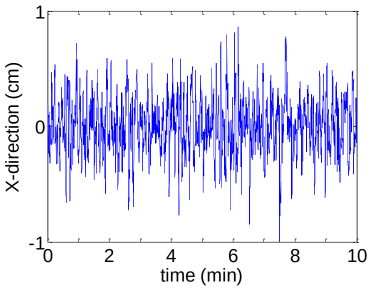
3.2.1 Optimization of GPS data for comparison

Before proceeding to the calculation of the torsional parameters, some observation should be highlighted regarding the comparison between results obtained by each set of data: the accelerometers data of #Nur08 were recorded in a time interval from 2:00 to 5:00 p.m., and during #Hag08 from 1:00 to 5:00 p.m., while, GPS data of #Mar09 were recorded from 9:00 to 12:00 p.m. This difference in recording times of data influences the accuracy of such comparison, because GPS accuracy - among the others- is influenced by the geometrical configuration of satellites overhead, which repeats itself every 24 hours; and the satellite configuration is strictly correlated to the GPS records. Therefore, taking the same time interval leads to neglect the errors in the GPS positioning that depend on the Geometric Dilution Of Precision (GDOP) (Casciati and Fuggini 2009). Based on these considerations, comparing such data has to refer to the same time interval during the day, unless one set of the data is modified by a conversion factor to be consistent with the other. Thus, the GPS measurements of #Nur08 is considered to be optimized according to a procedure based on assuming that; the standard deviation of GPS data recorded at two different time interval during a day is directly connected to the GDOP of the signal by the following relation

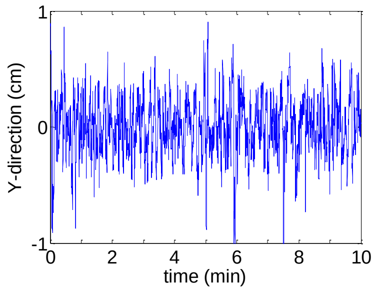
$$\sigma^*(\rho_i^j)/\sigma'(\rho_i^j) = f_{GDOP} \tag{1}$$

Where; f_{GDOP} is a GDOP index, and $\sigma^*(\rho_i^j)$ represents the standard deviation of the pseudo-range measurements (i.e., the calculated distances between satellites and receivers) at a certain time interval during the sidereal day, while, $\sigma'(\rho_i^j)$ represents the standard deviation of the pseudo-range measurements at a certain time interval during the day.

The condition of having GPS records obtained in the same time interval of other records obtained by accelerometers during the Nuri typhoon is achieved by the availability of data obtained by IT sensor from 2:00 to 5:00 p.m. Then, the GDOP of the GPS signal is defined as the ratio between the standard deviation of the data recorded from 2:00 to 5:00 p.m. and that of data recorded from 9:00 to 12:00 a.m. This is demonstrated in Fig. 14, in which the

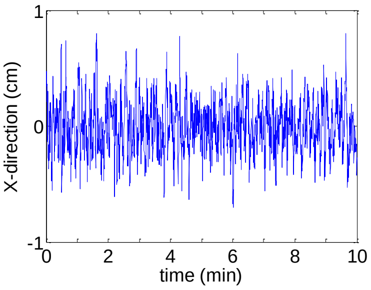


(a) Displacement time history in X-direction

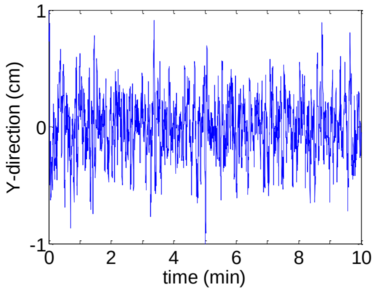


(b) Displacement time history in Y-direction

Fig. 15 Modified GPS displacement time histories recorded by N20



(a) Displacement time history in X-direction



(b) Displacement time history in Y-direction

Fig. 16 Modified GPS displacement time histories recorded by S9

East and North components by IT receiver of the two measuring periods are plotted with the ellipse having as radius the two values of root mean square. From these two graphs, a small but existing difference is evidenced.

Starting from this point, the GDOP conversion factor from 9-12 a.m. data to 2-5 p.m. data for the IT receiver is calculated equal to 0.87 for East component and 1.06 for North component. These factors apply also on the displacements of N20 and S9 receivers, so the GPS data can then be compared with accelerometers data. The modified time histories of N20 and S9 are drawn on Figs. 15 and 16, respectively.

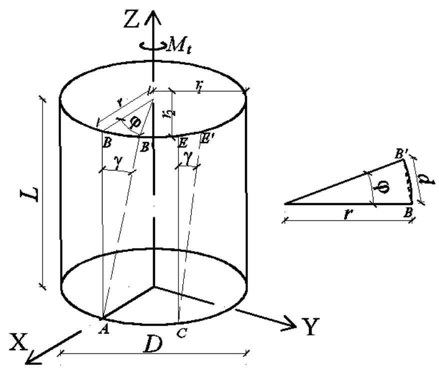


Fig. 17 Torsion of shaft cylinder with elliptical section

4. Detection of torsional behavior

As previously described, the Canton tower consists of two oval section tubes, therefore, in order to detect the torsional behavior by the available response data, the governing relation of a cylindrical shaft with an oval cross-section must be preliminarily introduced.

For a given uniform torque Mt on a cylindrical shaft (Fig. 17), the twist angle γ can be calculated as a function of the angle of rotation φ by the following equation:

$$\gamma = \frac{\phi}{L} \times \sqrt{\frac{r_1^2 + r_2^2}{2}} \tag{2}$$

Where r_1 and r_2 are the two radii of the oval cross section and L is the length of the shaft.

In the considered case study one GPS receiver is placed at the center of the oval inner tube, and two other sensors are located at a distance r from the center, and the line drawn between each of the two locations and the center is forming an angle θ with Y-axis, as shown in Fig. 18.

Assuming that; the measured data by the central GPS receiver measures does not contain any torsional contribution because it is located on the vertical axis of the shaft, and the displacement obtained at the other measuring points is a combination of displacements in two directions and rotation, the data collected from the three measuring points, shall allow the torsion detection of the tube.

The in-plane displacements, Δx and Δy, due to the pure rotation of the cross-section are simply calculated by subtracting the displacements obtained at the edges from the one simultaneously measured at the center, as follows

$$\begin{aligned} \Delta x &= X_0 - X_p \\ \Delta y &= Y_0 - Y_p \end{aligned} \tag{3}$$

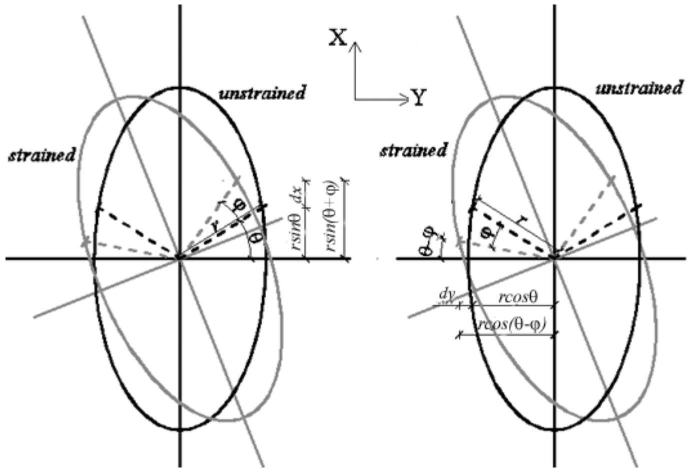


Fig. 18 Rotation of the inner tube oval section in the X-Y plane

where X_0 and Y_0 are the displacements measured by the central GPS receiver, and X_p and Y_p are the displacements measured at the edges in the corresponding directions. From Fig. 18, the following geometrical relationships apply

$$\begin{aligned} r.\cos(\theta-\phi) &= r.\cos\theta + \Delta x \\ r.\sin(\theta+\phi) &= r.\sin\theta + \Delta y \end{aligned} \tag{4}$$

Rearranging the two formulae of Eq. (4), the angle of rotation, φ, can be calculated from either one of the two in-plane displacements as follows

$$\begin{aligned} \phi &= \theta - \cos^{-1}\left(\cos\theta + \frac{\Delta x}{r}\right) \\ \phi &= \sin^{-1}\left(\sin\theta + \frac{\Delta y}{r}\right) - \theta \end{aligned} \tag{5}$$

Where r is the length of the line drawn from the position of the edge measuring point to the center of the oval, and θ is the inclination angle of the same line with respect to Y-axis.

4.1 Torsion under ambient vibration

In order to calculate the torsion induced in the tower in the absence of any extreme wind event, the parameters of the previously expressed equations should be identified. The in-plane displacements, Δx and Δy, due to the pure rotation of the cross-section are simply calculated by subtracting the displacements obtained at the edges measured by S9 receiver and N20 receiver (X_p and Y_p in Eq. (3), respectively) from the one simultaneously measured by IT receiver (X_0 and Y_0 in Eq. (3)). The angle of rotation can be calculated from either in-plane displacement, by Eq. (5); in which, r will be the distance between S9 or N20 receivers and IT receiver, and θ is measured equal to 30°.

The time history of the angle of rotation (φ) at the top plane section of the tower is plotted in Fig. 19; from which the maximum angle of rotation is around 0.1°. This value of φ corresponds to a maximum twist angle (γ) of 0.004°.

Aiming at validating the results obtained by GPS receivers, another elaboration for torsional detection under ambient vibration condition is developed using data obtained by the associated accelerometers. In May 19, 2009. The tower response was also recorded by accelerometers located at the top level of the tower; i.e. the same level of the GPS sensors considered previously. This ability of having also accelerometers measurements under the same condition allows a realistic evaluation of the GPS accuracy in detecting the torsional response of a flexible structure subjected to very low vibrations in the absence of significant excitation.

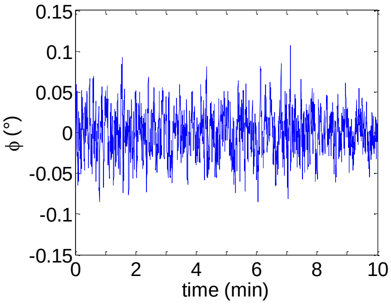


Fig. 19 Time history of rotation angle φ for #Mar09 tests

The data were integrated to obtain displacements following the previously explained procedure and the results with the corresponding new parameters were applied in Eqs. (2)-(5), and the resulted time history of φ is plotted in Fig. 20.

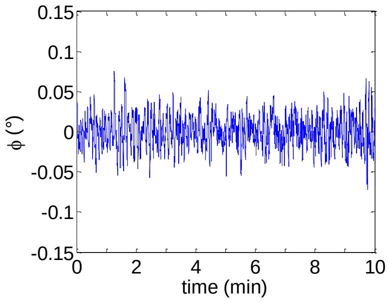


Fig. 20 Time history of rotation angle (φ) for #Mar09 tests (accelerometers measurements)

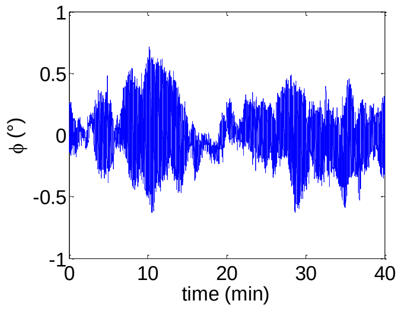


Fig. 21 Time history of angle of rotation of #Nur08

The maximum angle of rotation φ from Fig. 20 is around 0.08°, which is close but slightly lower than that calculated from responses measured by GPS receivers (0.1°). This value of φ corresponds to a maximum twist angle γ of 0.0035°. This means that in terms of maximum rotational angles induced results showed sufficient consistency when performed by the response data obtained from the two different sources.

4.2 Torsion under extreme wind events

When Nuri and Hagupit typhoons occurred only one GPS receiver was installed at the same height of two other accelerometers, which means obtained data had different types of sources, therefore; it is necessary to declare that; data processing of #Nur08 and #Hag08 indirectly involved some drawbacks mainly concerning; the synchronization of data obtained by two different sources, in addition to the integration needed prior to considering the accelerometers data. Based on these shortcomings, a suitable configuration of GPS sensors is conceived and realized, from which data are processed in the previous section.

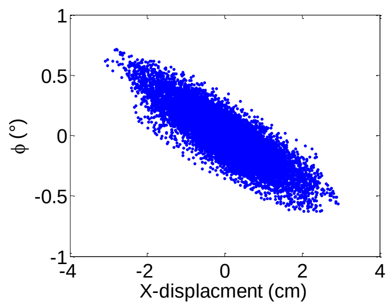
The time history of the torsional response of the tower in terms of the angle of rotation, φ, during Nuri typhoon is plotted in Fig. 21.

For the considered case, the values of r and θ are equal to 7303 mm and 30°, respectively. The maximum angle of rotation measured at the top level of the tower (443 m height) is about 0.71°, which corresponds to a relatively low twist angle of about 0.072°. The results showed a significant increase in the torsional response of the tower when exposed to Nuri typhoon, however, it worth's noting that using the GPS data of the rover sensor without removing the positioning errors elaborated using the measurements of the reference unit, would have probably led to wrong estimates of φ and γ (Faravelli *et al*. 2009).

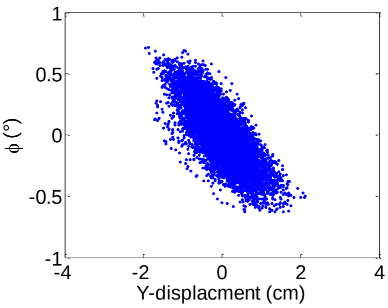
To investigate the effectiveness of sensor's locations in detecting the rotation angle (φ), its variation with the integrated displacements from the accelerations recorded is plotted in Fig. 22. The graphs shows that the variation of φ is more appreciable when related to the variation of X-direction displacements. This could be due to that X-direction corresponds to the longest axis of the inner tube oval cross-section.

The same procedure is repeated to calculate the torsional response of the tower during Hagupit typhoon to prove its effectiveness and robustness.

The time history of the torsional response of the tower



(a) X-direction



(b) Y-direction

Fig. 22 Variation of twist angle with displacements of #Nur08 (accelerometers data)

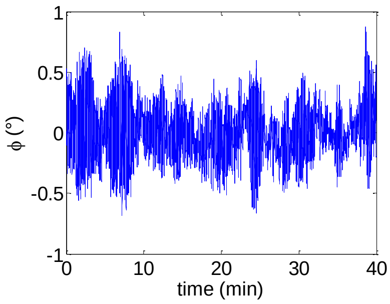


Fig. 23 Time history angle of rotation φ during the #Hag08 event

in terms of φ, using #Hag08 data is plotted in Fig. 23. The maximum calculated angle of rotation at the top level of the tower (448 m height) is about 0.87° corresponding to a twist angle of about 0.092°.

The last results agree with those obtained for #Nur08 data. Since the two wind events were having the same directions, and the maximum measured speed was almost the same (AlSaleh 20011), also the tower height was not significantly increased (5 m higher in case of #Hag08), it derives that the values of the torsional parameters have to be almost equal. In addition, by comparing the two Figures (Figs. 21 and 23) it can be seen that they are in good agreement, thus proving the effectiveness of the torsional detection.

5. Conclusions

This study presents a solution based on GPS and accelerometers sensors within the structural monitoring of the Canton Tower. It investigates the detection of torsional response of the super-tall tower during typhoon wind events through processing SHM data obtained under two different conditions:

(i) During ambient vibrations condition, when a GPS network consisting of three rover receivers placed at the top level of the tower.
(ii) During Nuri and Hagupit typhoons, when a rover GPS and two uni-axial accelerometers were installed on the top level of the tower.

The experimental measurements taken from the sensors (for the two scenarios) are analyzed to calculate two main torsional parameters: the angle of rotation (φ) of the oval cross section, and the twist angel γ of the inner shaft cylinder. The angle of rotation is plotted as a function of time, taking into account the sensors measurements and their location, as requested by one task of the benchmark on the Canton tower.

The results of torsion under typhoon events are affected by two main issues: (i) the use of two different types of sensors (accelerometers and GPS) working independently each of the other, thus reducing the accuracy by the non-synchronization associated to the recorded data; (ii) the integration process from accelerations to displacements. However, these issues can be overcome by using a series of GPS sensors instead.

The GPS topology on the top level of the tower is chosen as follows: one antenna is located in the center of the inner tube and one (or more than one) at the edges (instead of accelerometers). Indeed, it is required that the baselines connecting the reference and the rovers' receivers are oriented along either the X-axis or the Y-axis. The use of even only one GPS receiver at the edge, also allows removing the suspected non-synchronization of data, which may have occurred when the accelerometers had to be considered. Furthermore, as the GPS is not only a displacement sensor but also a time sensor (Casciati and Fuggini 2009), this probably suggests using the GPS sensors for time synchronization.

Another purpose of this study was to analyze and compare the torsional behavior of the tower with and without significant wind events. To this aim, a factitious procedure has to be applied when the data from GPS and other sensors are not recorded at the same time-period of the day. Based on this fact; it is recommended to convert also the response data under typhoons in order to achieve more reliable comparison with the response under ambient vibration. Therefore, the recorded GPS displacements of #Mar09 have been modified by a conversion factor, in order to recalculate the GPS displacements as they would have been recorded at the required time period (from 2.00 to 2.10 p.m).

A simple mathematical approach is then adopted to obtain the time history of twist angle under ambient vibration as well as during the typhoon events.

Results of this contribution, firstly confirmed the effectiveness of GPS receivers for system identification purposes proved by the resulted fundamental frequencies for the tower from the GPS data typical to those obtained by accelerometers. Secondly, the torsional response of the tower obtained by GPS receivers – defined by the time history of the twist angle – showed acceptable correspondence to that obtained by combining data from both resources.

Acknowledgments

The authors acknowledge Professor Ni and his team at the Department of Civil and Structural Engineering of the Hong Kong Polytechnic University for their collaboration in providing the experimental measurements. This study was supported by a grant from the University of Pavia.

References

AlSaleh, R. (2011), "Verification of wind pressure and wind induced response of a supertall structure using a long-term structural health monitoring system", Ph.D. Dissertation; University of Pavia, Pavia, Italy.

AlSaleh, R., Casciati, F. and Fuggini, C. (2009), "Detecting the torsional behavior of a tall building by GPS receivers", *Proceedings of the COMPDYN 2009, ECCOMAS Thematic Conference on Computational Methods in Structural Dynamics and Earthquake Engineering*, Rhodes, Greece, CD-ROM. (article CD438)

Casciati, F. and Fuggini, C. (2009), "Engineering vibration monitoring by GPS: long duration records", *Earthq. Eng. Eng. Vib.*, **8**(3), 459-467. https://doi.org/10.1007/s11803-009-9058-8

Casciati, F. and Fuggini, C. (2011), "Monitoring a steel building using GPS sensors", *Smart Struct. Syst., Int. J.*, **7**(5), 349-363. https://doi.org/10.12989/sss.2011.7.5.349

Casciati, F., AlSaleh, R. and Fuggini, C. (2009), "GPS-Based SHM of a tall building: torsional effects", *Proceedings of the 7th International Workshop on Structural Health Monitoring 2009*, Stanford University, Stanford, CA, USA, pp. 340-347.

Elbeltagi, E., Kaloop, M.R. and Elnabwy, M.T. (2014), "Structural health monitoring system using GPS for sustainable bridges", *Zaytoonah University International Engineering Conference on Design and Innovation in Sustainability* (*ZEC Infrastructure*), Amman, Jordan.

Faravelli, L., Casciati, S. and Fuggini, C. (2009), "Full-scale experiment using GPS sensors for dynamic tests", *Proceedings of the XIX Congress AIMETA*, Ancona, Italy, CD-ROM.

Gorski, P. (2017), "Dynamic characteristic of tall industrial chimney estimated from GPS measurement and frequency domain decomposition", *Eng. Struct.*, **148**, 277-292. https://doi.org/10.1016/j.engstruct.2017.06.066

Gorski, P. and Konopka, E. (2009), "Monitoring of tall slender structures by GPS measurements", *Wind Struct., Int. J.*, **12**(5), 401-412. https://doi.org/10.12989/was.2009.12.5.401

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*, **12**, 1014-1034. https://doi.org/10.3390/s120101014

Kaloop, M.R. (2012), "Bridge safety monitoring based-GPS technique: case study Zhujiang Huangpu bridge", *Smart Struct. Syst., Int. J.*, **9**(6), 473-487. https://doi.org/10.12989/sss.2012.9.6.473

Kaloop, M.R., Elbeltagi, E., Hu, J.W. and Elrefai, A. (2017), "Recent advances of structures monitoring and evaluation using GPS-time series monitoring systems: A Review", *Int. J. Geo-Info.*, **6**, 382-399. https://doi.org/10.3390/ijgi6120382

Kijewsji-Correa, T. and Kochly, M. (2007), "Monitoring the wind-induced response of tall buildings: GPS performance and the issue of multipath effects", *J. Wind Eng. Indust. Aerodyn.*, **95**, 1176-1198. https://doi.org/10.1016/j.jweia.2007.02.002

Kijewsji-Correa, T., Kareem, A. and Kochly, M. (2006), "Experimental Verification and Full-Scale Deployment of Global Positioning Systems to Monitor the Dynamic Response of Tall Buildings", *J. Struct. Eng.*, **132**(8), 1242-1253. https://doi.org/10.1061/(ASCE)0733-9445(2006)132:8(1242)

Kim, R., Billie J., Spencer, F., Nagayama, J.T. and Mechitov, K. (2016), "Synchronized sensing for wireless monitoring of large structures", *Smart Struct. Syst., Int. J.*, **18**(5), 885-909. https://doi.org/10.12989/sss.2016.18.5.885

Kuang, C.L., Kwok, K.C., Hitchcock, P.A. and Ding, X.A. (2011). "Wind-induced response characteristics of a tall building from GPS and accelerometer measurements", *Positioning*, **2**, 1-13.

Li, X., Rizos, C., Ge, L., Tamura, Y. and Yoshida, A. (2005), "The Complementary characteristics of GPS and Accelerometer in Monitoring Structural Deformation", *Proceedings of the US Institute of Navigation National Technical Meeting*, San Diego, CA, USA, pp. 911-920.

Li, Q.S., Xiao, Y.Q., Fu, J.Y. and Li, Z.N. (2007), "Full-scale measurements of wind effects on the Jin Mao building", *J. Wind Eng. Indust. Aerodyn.*, **95**, 455-466. https://doi.org/10.1016/j.jweia.2006.09.002

Moschas, F., Psimoulis, P.A. and Stiros, S.C. (2013), "GPS/RTS data fusion to overcome signal deficiencies in certain bridge dynamic monitoring projects", *Smart Struct. Syst., Int. J.*, **12**(3), 251-269. https://doi.org/10.12989/sss.2013.12.3_4.251

Ni, Y.Q. and Zhou, H.F. (2010), "Guangzhou New TV Tower: Integrated Structural Health Monitoring and Vibration Control", *Structures Congress ASCE*, pp. 3155-3164.

Ni, Y.Q., Xia, Y., Liao, W.Y. and Zhang, P. (2008), "Development of a structural health monitoring system for guangzhou new TV tower", *Adv. Sci. Technol.*, **56**, 414-419. https://doi.org/10.4028/www.scientific.net/AST.56.414

Ni, Y.Q., Xia, Y., Liao, W.Y. and Ko, J.M. (2009a), "Technology innovation in developing the structural health monitoring system for Guangzhou New TV Tower", *Struct. Control Heath Monitor.*, **16**(1), 73-98. https://doi.org/10.1002/stc.303

Ni, Y.Q., Xia, Y., Chen, W.H., Lu, Z.R., Liao, W.Y. and Ko, J.M. (2009b), "Monitoring of wind properties and dynamic responses of a supertall structure during typhoon periods", *Proceedings of the 4th International Conference on Structural Health Monitoring on Intelligent Infrastructure* (*SHMII-4*), Zurich, Switzerland.

Pehlivan, H. (2018), "Frequency analysis of GPS data for structural health monitoring observations", *Struct. Eng. Mech., Int. J.*, **66**(2), 185-193. https://doi.org/10.12989/sem.2018.66.2.185

Peppa, I., Psimoulis, P. and Meng, X. (2018), "Using the signal-to-noise ratio of GPS records to detect motion of structures", *Struct. Control Health Monitor.*, **25**(2), e2080. https://doi.org/10.1002/stc.2080

Psimoulis, P., Houlié, N., Meindl, M. and Rothacher, M. (2015), "Consistency of PPP GPS and strong-motion records: case study of Mw9.0 Tohoku-Oki 2011 earthquake", *Smart Struct. Syst., Int. J.*, **16**(2), 347-366. https://doi.org/10.12989/sss.2015.16.2.347

Xia, Y., Ni, Y.Q., Ko, J.M. and Chen, H.B. (2008), "ANCRiSST benchmark problem on structural health Monitoring of high-rise slender structures", *Proceedings of the 4th International Workshop on Advanced Smart Materials and Smart Structures Technologies*, Tokyo, Japan.

Yi, T.H., Li, H.N. and Gu, M. (2013), "Wavelet based multi-step filtering method for bridge health monitoring using GPS and accelerometer", *Smart Struct. Syst., Int. J.*, **11**(4), 331-348. https://doi.org/10.12989/sss.2013.11.4.331

Yi, T.H., Ye, X.W., Li, H.N. and Guo, Q. (2017), "Outlier detection of GPS monitoring data using relational analysis and negative selection algorithm", *Smart Struct. Syst., Int. J.*, **20**(2), 219-229. https://doi.org/10.12989/sss.2017.20.2.219

FC