Full-scale experiment using GPS sensors for dynamic tests

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SUMMARY. Monitoring the performance of any structure requires to measure, in real time , the change of position of its critical points. Different techniques can be useful for this purpose and each one presents some advantages and drawbacks. The techniques based on the satellite positioning systems (GPS, GLONASS and the future GALILEO) seem to be very promising at least for structures characterized by a high natural period. The GPS in particular provides sampling rates up to 20Hz sufficient to track real time dynamic displacements of flexible structures with high accuracy of the order of the sub-centimetre [1-2]. Its performance is independent of atmospheric conditions, temperature variations and visibility of the monitored object. In this paper, the elaboration of the measurements recorded from dual frequency GPS receivers during a full scale experimental campaign, in which the dynamic tests were conducted with GPS sensors, is reported.

Structures like tall buildings are particularly sensitive to oscillations produced by different sources of dynamic actions, such as earthquakes, wind and typhoon. In particular, the wind forces induce both longitudinal and perpendicular displacements with respect to the wind direction, but they also produce torsional effects which are more complex to be detected by full-scale experimental tests. To track the horizontal in-plane movements and the torsional rotations of the in-plane sections of such flexible structures, two main items have to be considered: the first is the choice of the most suitable sensor topology (i.e., location, installation, and combination of the GPS receivers) in order to gain information on the response of the structure; the second is the methodology used to process the recorded GPS data. The Guangzhou New TV Tower [3], which is currently being constructed in Guangzhou, China, is considered as case study. The elaboration of the rather long records provided by the GPS, placed at the top of the tower during strong wind events such as typhoons, is carried out.

1 INTRODUCTION

In the dynamic monitoring of civil structures, satellite systems, such as the American Global Positioning System (GPS), are being proposed as an alternative to the common accelerometers, in particular to measure the dynamic response of structures characterized by a high natural period. [1-4]. High-precision GPS technology has been deployed to monitor the wind-induced deformations of tall flexible buildings [5] and to asses the vibrations of suspension and cable-stayed bridges [6-7]. By installing the GPS receivers at key locations, many applications were able to capture both the static and dynamic displacements of a structure, in real time and in all weather conditions [8].

In particular, the knowledge of the relative displacements enables to assess the drift values and the stress conditions of a structure. The GPS provides them directly, without single or double integrations as velocimeters and accelerometers require, thus removing all the problems related to the integration process [9]. Moreover, the GPS offers the advantages of operability in all weather conditions, temperature independence and suitability to continuous long term acquisitions.

Among all the possible applications, the GPS network can be used for the Structural Health Monitoring (SHM) of tall and flexible structures which are particularly sensitive to the oscillations produced by wind actions. Wind forces not only induce a displacement response in both the longitudinal and transversal wind directions, but they also produce torsional effects which are more complex to be detected during full-scale experimental tests. These torsional effects are mainly due to the fact that the center of mass does not coincide with the stiffness center of the building. To detect the torsional induced effects, the sensors placement on the structure must be designed in order to identify a preferable topology (i.e., combination and locations of the sensors) able to provide information on the torsional response. In this manner, a network of GPS receivers, installed at the top of a tall building can detect with sufficient accuracy the induced torsional response of the structure.

In the present work, the feasibility of Structural Health Monitoring via an integrated network made of one GPS and several accelerometers is investigated by considering the Guangzhou New TV Tower (GNTVT) in China, as case study. In particular, the displacement response of the tower has been acquired by using one rover GPS placed at the top level of the tower,, and two uni-axial accelerometers placed at the same level of the GPS receiver. Particular attention is devoted to the development of a methodology to process these displacement data in order to detect the torsional mode shapes of the building.

2 EXPERIMENTAL CONFIGURATION OF THE GNTVT

The Guangzhou New TV Tower (GNTVT), currently being constructed in Guangzhou (China) to broadcast the 16th Asian Games in 2010, is a super-tall structure with a height of 610 m [10]. This "tube-in-tube" structure is made of a reinforced concrete inner tube and a steel outer tube with concrete-filled-tube (CFT) columns. In particular, the outer tube consists of 24 CFT columns, which are uniformly spaced forming an oval and are inclined with respect to the vertical direction. The resulting oval cross-section of the outer tube varies along the height of the tower; it decreases from 50×80 m at ground level to the minimum dimensions of 20.65×27.5 m at the height of 280 m, and then it progressively increases up to 41×55 m at the top level of the tube (454 m of height). The columns are transversely connected by steel rings and bracings. The inner tube has an oval shape as well, with constant in plan dimensions of 14×17 m (Figure 1).

A Structural Health Monitoring (SHM) system of the tower, consisting of over 600 sensors, has been designed and implemented by the Hong Kong Polytechnic University for both in-construction and in-service real-time monitoring. For this purpose, an SHM benchmark problem was conceived [11]. One task of this benchmark problem is the development of a performance-based optimal sensor placement for SHM. In the present study, the attention is focused on the identification of a preferable topology (i.e., combination and locations of the sensors) able to provide information on the torsional response of the structure when exposed to strong wind events, such as typhoons, whose occurrence is frequent in the considered geographic area.

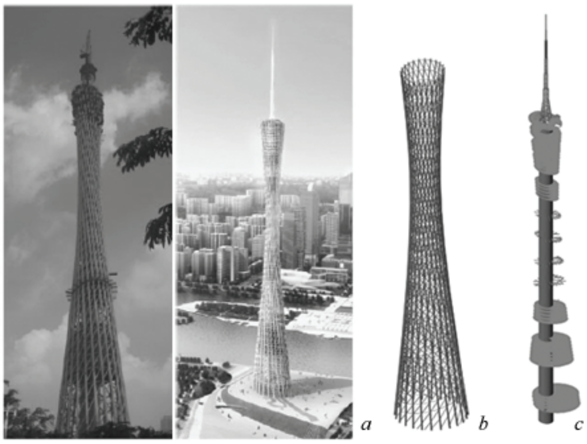

Figure 1: (a) The GNTVT during its construction phase (left) and a rendering view of the tower (right); (b) the external tube; (c) the interior tube, the floors, the connection girders and the mast .

For this purpose, the data recorded on site by the GPS receivers and by the accelerometers during the Nuri typhoon, which occurred on August 22, 2008, are analyzed to achieve more information on the torsional response of the GNTVT. During the Nuri typhoon one reference GPS was placed at the base of the tower and one rover GPS was set at the top. Two uni-axial accelerometers were located nearby, one along the West-East direction (which is denoted as W-E acc.) and the second along the North-South direction (which is denoted as N-S acc.).

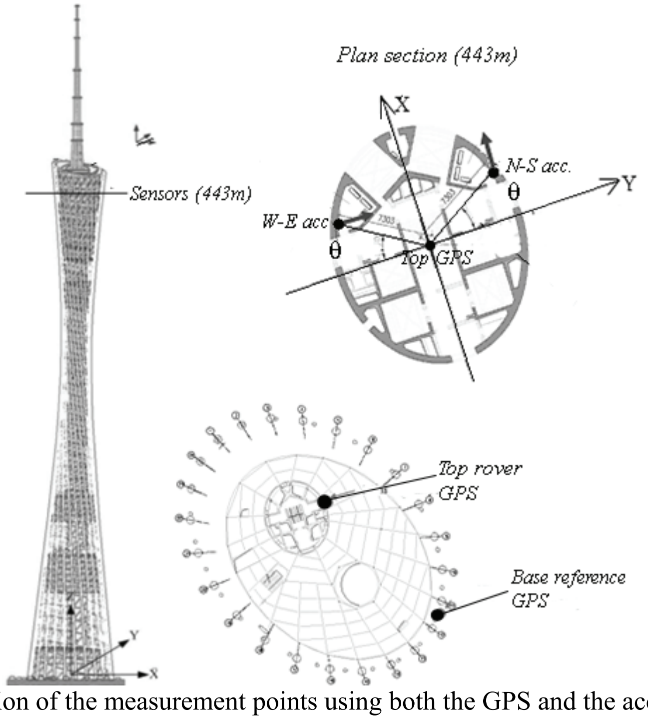

Figure 2: Location of the measurement points using both the GPS and the accelerometers as sensors.

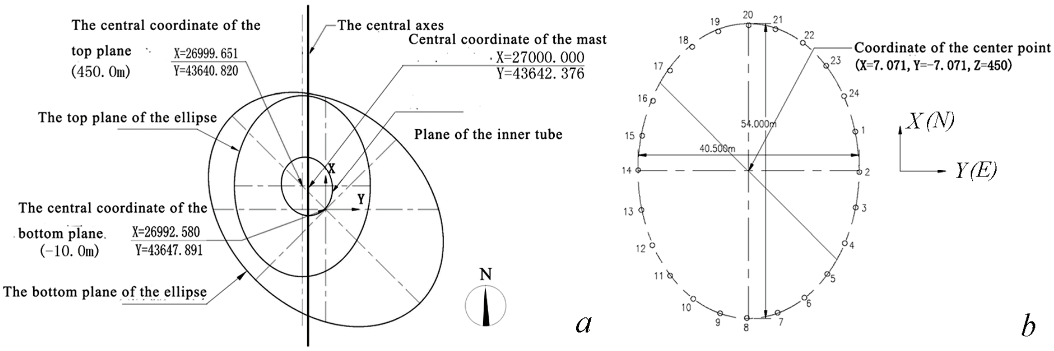

Figure 3: (a) Geometrical representation of the oval cross-sections of the tower. (b) geometry and reference axes of the cross-section at the height where the GPS and the accelerometer are placed.

In Figure 2, the selected topology of the sensors network is evidenced: the rover GPS is placed in the center of the elliptical cross-section, serving as reference point for the torsion measurements, while the two accelerometers are placed at the opposite edges of this section, in two points forming an angle, θ ,with the short axis, *Y*. The *X* and *Y* axes drawn in Figure 2 are, indeed, the directions along the long radius and the short radius of the oval cross-section, respectively. The *X*-direction measurements obtained from accelerometers also correspond to the North coordinates of the GPS measuring point; while the measurements in the *Y*-direction correspond to the East coordinates. This correspondence depends on the orientation of the oval cross-section which changes with the tower height. It is shown Figure 3 for those cross-sections oriented as the considered one at the top of the tower.

The data processing method described in the following is applied to the records obtained during the Nuri typhoon, but it can also be used to treat the data collected during other wind events, since it represent a general procedure to obtain the torsional deformation of the tower. The future availability of records obtained during no wind events will possibly enable the authors to identify the torsional state to be regarded as initial configuration, unstrained by wind effects [12]. For this purpose, the GPS data have to be recorded for several days, covering the same hours of the day during which the typhoon occurred (i.e., from 2 to 5 p.m.). This requirement is a direct consequence of the fact that the GPS satellite configuration repeats itself every 24 hours. Hence, it must be the same for the same time interval of different days. Since the satellite configuration is strictly correlated to the GPS in-plane precision, considering the same time interval enables to neglect the errors in the GPS positioning which depend on the so called "geometric dilution of precision" (GDOP).

3 TORSIONAL EFFECTS ON A CYLINDRICAL SHAPE

As described in the previous Section, the GNTVT tower is a "tube-in-tube structure", with both tubes of oval cross-section (Figures 2, 3). In order to detect the torsional behavior of the tower using the in-site experimental data, the governing relations of the torsion of cylindrical shaft with oval cross-section must be preliminarily introduced. For a given uniform torque, M_t, on a cylinder shaft (Figure 4), the twist angle γ can be calculated as a function of the angle of rotation φ by means of the following equation:

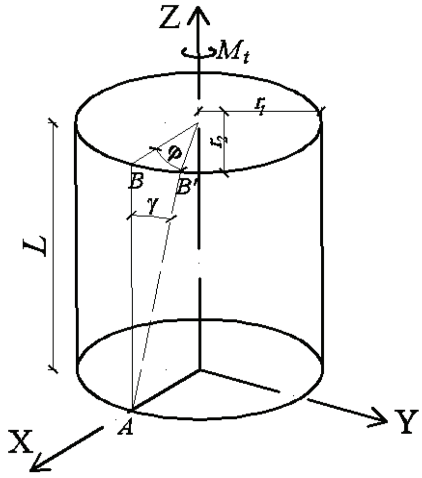

Figure 4: Torsion of a cylindrical shaft with an oval cross-section.

$$\gamma = \frac{\varphi}{L} * \sqrt{\frac{r_1^2 + r_2^2}{2}} \tag{1}$$

where r_1 and r_2 are the two radii of oval cross-section and L is the length of the cylinder.

In the considered case study; the GPS receiver is placed at the center of the oval, while the two accelerometers are located at a distance r from it, forming an angle ,θ, with the Y axis. The GPS measures the displacements of the center of the cross-section in the two horizontal directions, with respect to its original position when the tower is at rest. The locations of the accelerometers imply that their measurements can provide a combined displacement, resulting from the displacements in both directions and the rotation around the vertical axis of the tower. Utilizing the data collected from both the accelerometers at the far edges of the tower and the GPS receiver at the center of its section, the torsional angle is eventually calculated.

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:

$$\begin{aligned} \Delta x &= X_0 - X_p \\ \Delta y &= Y_0 - Y_p \end{aligned} \tag{2}$$

where X_0 and Y_0 are the displacements measured by the GPS receiver, and X_p and Y_p are the displacements calculated from the accelerometers in the corresponding directions.

As shown in Figure 5, the following geometrical relationships hold:

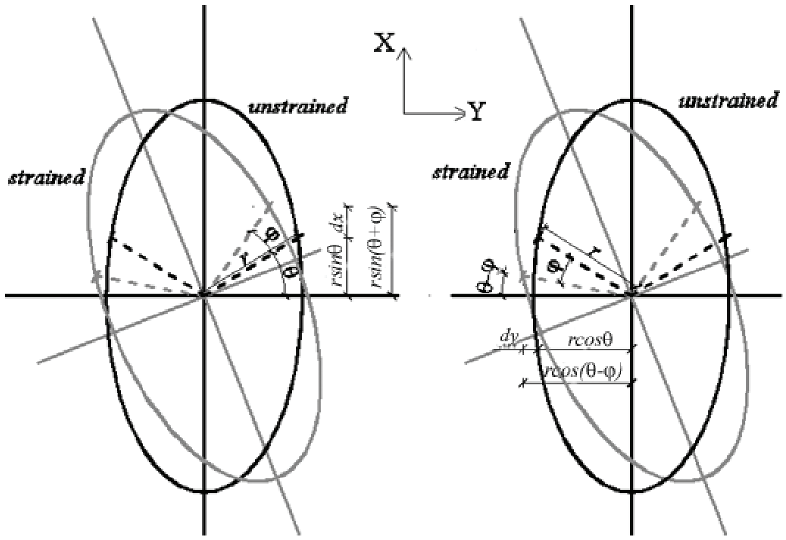

Figure 5: Torsional rotation of the elliptical section.

$$r\,cos(\theta-\varphi)=r\,cos\,\theta+\Delta x$$
$$r\,sin(\theta+\varphi)=r\,sin\,\theta+\Delta y \tag{3}$$

By rearranging the two formulae of Equation (3), the angle of rotation, φ, can be calculated from either one of the two in-plane displacements:

$$\varphi=\theta-cos^{-1}\left(cos\,\theta+\frac{\Delta x}{\gamma}\right)$$
$$\varphi=sin^{-1}\left(sin\,\theta+\frac{\Delta y}{\gamma}\right)-\theta \tag{4}$$

where r is the length of the lines drawn from the positions of the accelerometers to the center of the oval, and θ is the inclination angle of the same line with respect to the X axis. For the considered case-study, the values of r and θ are equal to 7303 mm and 30º, respectively, as specified in Figure 2.

4 DATA ANALYSIS

A segment with duration of 40 minutes is extracted from the data recorded by the GPS unit and by the accelerometers during the Nuri Typhoon. The GPS sampling rate is 5 Hz, while the sampling rate of the two uni-axial accelerometers is 50 Hz. It is worth noting that the displacement time histories of the GPS rover receiver are calculated with respect to the position of the receiver at the base of the tower, which is used as a fixed reference, in a differential global positioning mode (DGPS). This procedure enables to remove the measurement errors of the moving receiver, which may affect the precision of the torsional parameters calculation.

The displacement time histories in both the X and Y directions are drawn in Figures 6 and 7. The two graphs of Figure 6 refer to the displacements recorded by the GPS; while the two graphs of Figure 7 refer to the displacements derived from the recorded accelerations. Since the GPS and the accelerometer signals are independently recorded, a suitable synchronization is strongly needed in order to perform a comparative analysis.

The time histories of the torsional response of the tower in terms of both the angle of rotation, φ, and the twist angle, γ, due to the occurrence of the Nuri typhoon are plotted in Figure 8. The maximum angle of rotation at the top of the GNTVT (i.e., at the height of 443m) is about 1.2 degrees, which corresponds -as expected- to a relatively low twist angle of about 0.1 degrees. Since the angles of rotation are small, it is worth noting that using the GPS data of the rover sensor without removing the positioning errors elaborated from the measurements of the reference unit, would have probably led to wrong values of φ and γ, which would not been representative of the real ones.

To investigate how the locations of the sensors influence the values of the angle of rotation, φ, its variation with the displacements derived from the accelerations recorded is plotted in Figure 9. These graphs suggest that the variation of φ is more appreciable along the *X* direction, which also corresponds to the longest axis of the oval cross-section located at the height of 443m.

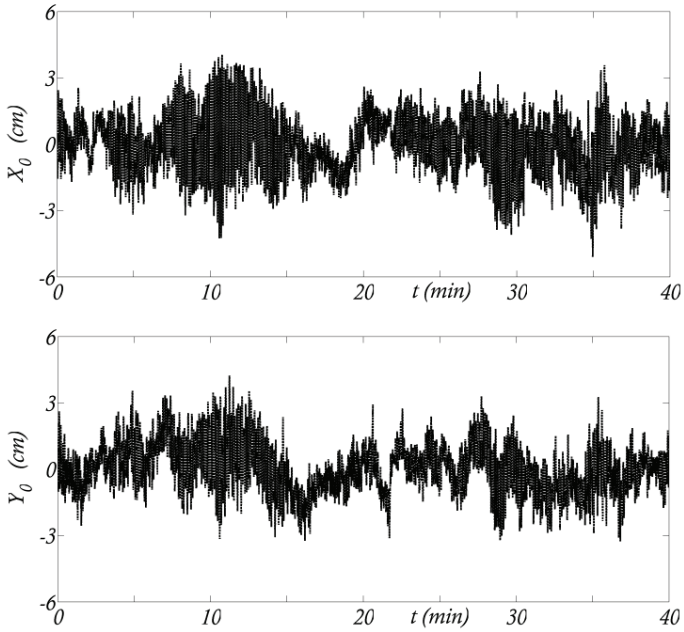

Figure 6: GPS in-plane displacement time histories during the Nuri typhoon event: measurements along *X* (top), and measurements along *Y* (bottom).

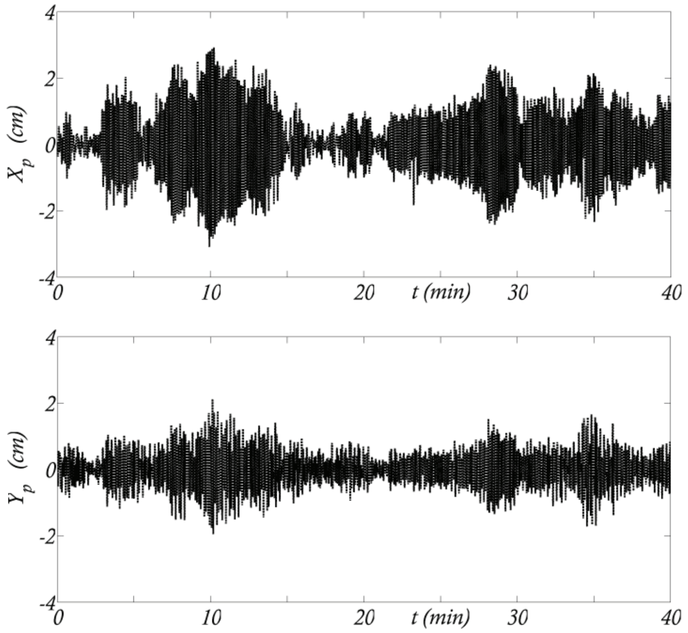

Figure 7: Accelerometers derived displacement time histories during the Nuri typhoon event: measurements taken along *X* (top), and along *Y* (bottom).

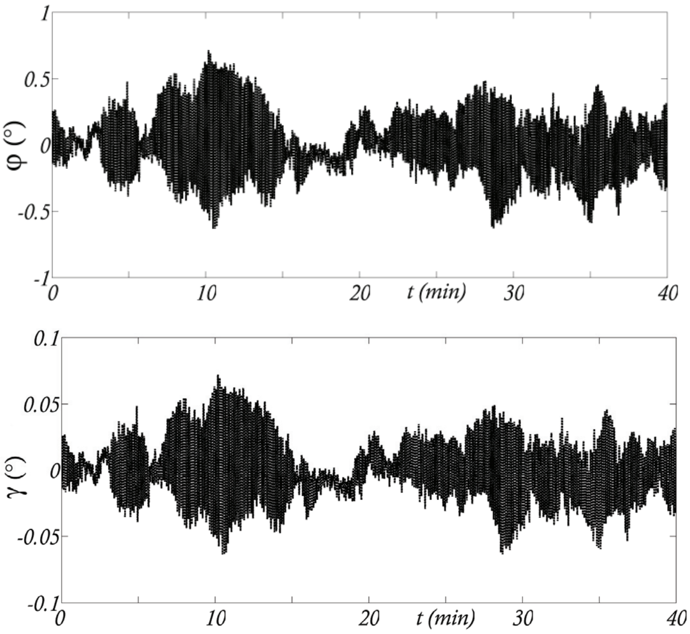

Figure 8: Time histories of the torsional response parameters during the Nuri typhoon event: angle of rotation φ (top); twist angle γ (bottom)

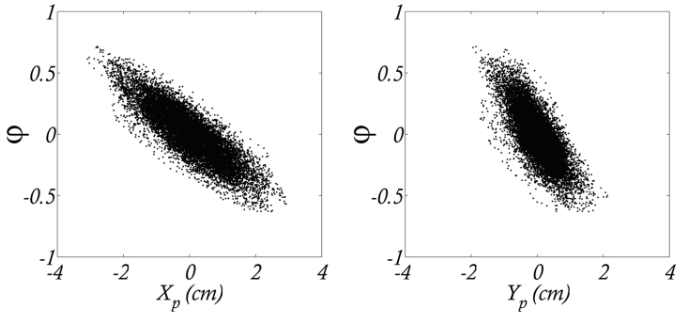

Figure 9: Variation of the angle of rotation φ with respect to the X (left) and Y (right) displacements derived from the accelerations measurements.

5 CONCLUSIONS

A procedure to detect the torsional response of a tall cylindrical tower with oval cross-section due to wind loading is outlined. The data recorded, during one of these events (the Nuri typhoon) by a rover GPS and two uni-axial accelerometers placed at the top of the GNTTV, are analyzed. Two torsional parameters are calculated as a function of time: the angle of rotation of the oval cross-section and the twist angle of the inner shaft cylinder. Their dependence on the sensors measurements and their locations is also investigated.

The accuracy of the results is affected by several issues which must be taken under consideration: i) the different types of sensors that have been used (accelerometers and GPS), which work independently from each other, thus giving rise to a possible non synchronization of the recorded data; ii) the errors associated with the integration of the acceleration measurements in order to obtain the required displacements. Furthermore, the displacements collected by the rover GPS receiver must be modified in function of the positioning errors, which can be calculated by using a reference base receiver.

The effects due to the integration process and to the non synchronization among the sensors could be removed by using several GPS sensors: one located at the center of the inner tube and the other ones at the edges of the tower (instead of the accelerometers), with the baselines connecting the two receivers to the center either oriented along the X or the Y axis. Having more than one GPS unit at the top level would also reduce the uncertainty in the displacement measurements and it would enable a more accurate estimate of how precise and useful could the GPS be in detecting the torsional movements.

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