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Preliminary evaluation of precise inclination sensor and GPS for monitoring full-scale dynamic response of a tall reinforced concrete building

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Abstract. It is necessary to use different sensors in an integrated manner – GPS, accelerometer, inclination sensor and so on – in order to monitor and identify static, quasi-static and resonant response of tall buildings subjected to wind loading. There are some differences among these sensors with respect to data sampling rate, data quality, and their measurement accuracy. Therefore, using different sensors together for a monitoring project is important because of the complementary nature of each sensor. In this study, the behaviour of a tall reinforced concrete building (30 stories high) under wind load has been monitored using GPS and inclination sensors. This paper assesses the dynamic measurement quality and reliability of inclinometers for building monitoring applications, and discusses the strengths and weaknesses of GPS vis-a-vis the use of inclination sensors for monitoring the dynamic response of tall buildings under wind load. Data collected by these sensors have been analysed in the time and frequency domains. It was found that GPS observations were distorted by multipath caused by a reflecting surface on top of the building. From the analyses in the frequency domain, the 1st mode natural frequencies of the building determined from both sensors agree very well with each other. The discrepancy of this measured 1st mode natural frequency compared to that derived from FEM (Finite Element Model) prediction is 7%.

Keywords. Full-scale monitoring, GPS and inclination sensor, tall building, wind load, dynamic response.

1. Introduction

Relative displacement is a key to assessing structural dynamic response. Dynamic stability analysis is essential for structures subject to non-conservative loads, such as wind or pulsating forces. Structures loaded in this manner may appear to be stable according to static analysis, while in reality they may fail due to vibrations of ever increasing amplitude or some other accelerated motion (Bazant & Cedolin 2003). Thus direct measurement of the dynamic displacement of the structure in the horizontal plane is very important for assessing its vibration amplitude. One of the most popular geotechnical instruments is the accelerometer, which is used widely for monitoring engineering structures such as tall buildings, towers and suspension bridges. With accelerometer measured acceleration response, it is necessary to implement a double integration process to derive displacements. For this reason, GPS is a valuable tool to measure the displacement directly. Lovse et al. (1995) studied the performance of GPS for monitoring tall structures. Celebi et al. (1997, 1999) also discussed the concept and described successful preliminary tests to demonstrate the technical feasibility of using GPS for continuous monitoring of structures. Tamura et al. (2002) reported that RTK-GPS could measure displacements when the vibration frequency was less than 2 Hz and the displacement amplitude was greater than 2 cm. Numerous studies can be found in the literature concerning the use of GPS and accelerometers to monitor dynamic structural vibration due to various loading conditions (e.g. Lovse et al. 1995, Ogaja et al. 2003, Brownjohn 2004, Çelebi et al. 2002, Roberts et al. 2000, 2004, Hristopulos et al. 2007, Barnes et al. 2004, Bereuer et al. 2008, Li et al. 2008, Park et al. 2008). Li et al. (2006 a–b–c) studied the integration of GPS and accelerometers for the purpose of monitoring static, quasi-static and dynamic components of engineering structures. Very recently, the application of Robotic Total Station, GPS and Terrestrial Laser Scanning for dynamic measurement of displacement has been reported on (Gikas and Daskalakis 2008, 2009, Psimoulis and Stiros 2007, 2008).

Many engineering structures such as tall buildings, towers, cable-suspended bridges are vulnerable to wind-induced vibration. The trend in constructing higher buildings and longer bridges with less material has contributed to a new generation of wind-sensitive structures that the modern day structural engineer must cope with (Liu 1991).

Wind-induced structural vibration depends to a large extent on the characteristic of structures. The

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three most relevant characteristics are mode shapes, stiffness, and damping values. In addition to the structural characteristics, wind-induced structural vibration also depends on the characteristics of the wind itself (Ibid 1991). Wind-induced responses of a structure generally consist of three components: (a) a static component due to mean wind force, (b) a quasi-static component caused by the low frequency wind force fluctuation, and (c) a resonant component caused by the wind force fluctuation near the structure's first mode natural frequency (Tamura 2003). For instance, the turbulence in wind buffeting on structures causes vibration. Buffeting can be especially serious if the dominant frequency of turbulence approaches the natural frequency of the structure.

Full-scale measurement is considered to be the most reliable method for evaluating wind effect on, and determining the dynamic characteristics of, building and structures. During the last two decades a revolution in data handling and collection has made possible enormous strides in full-scale measurement of the dynamic behaviour of tall buildings.

This paper presents preliminary results of the measurement and analysis of a reinforced concrete tall building under a small-scale wind loading. The full-scale measurements were obtained from the integrated system of GPS, inclination sensor and anemometer. The measured wind-induced response of the building has been analysed in both the time and frequency domains in order to detect the natural frequency of the building, and to compare the measured frequency with the predicted value using a Finite Element Model (FEM). The strengths and weaknesses of GPS vis-a-vis the use of inclination sensors are discussed for monitoring the dynamic response of tall buildings under a small-scale wind loading conditions. The paper ends with some preliminary conclusions and suggestions for future work.

2. Structure and instrumentation

The structure investigated in this study is a 30-storey tall reinforced concrete building in the city of Konya, Turkey. The building structure consists of 44 columns of different sizes and 2 shear-nucleuses (core construction). The building's height is approximately 100 m above the street level. The foundation area of the building is 685 m^2 with a floor plan approximating an ellipse (Yigit et al. 2008, 2010). The plan view and picture of the building can be seen in Figure 1.

GPS, inclinometer and anemometer have been deployed on the building in order to monitor its dynamic response to various loading conditions, such as wind and earthquake. Schematic overview of the GPS, inclinometer and anemometer sensors array is shown in Figure 2.

A GPS antenna was installed on the north-east corner of the top of the building in order to monitor the actual tip displacement of the building. In this monitoring project, the GPS system consisted of two Topcon HiPer Pro receivers, one was set up as a rover station on the top of the building, and the other as a base station on a pillar with good sky view about 1 km away from the building.

Two inclination sensors have been deployed on the building to monitor its inclination. The biaxial inclination sensors, the Leica Nivel 220 instruments, have been installed at the 21st and 26th floors on one of the shear-nucleus, which are on the same side as the GPS (to allow for cross-comparison of measurements), as indicated in Figure 2.

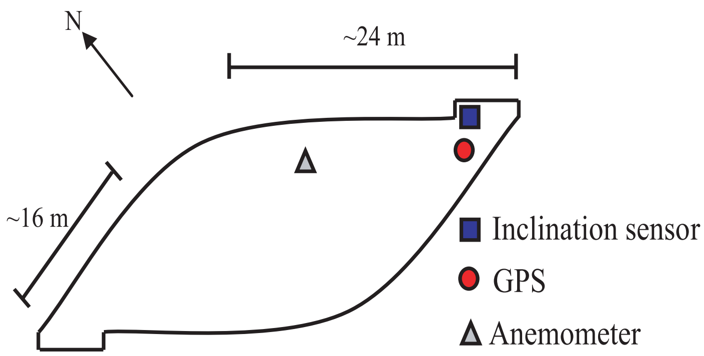

Figure 1: Plan view and photographs of the Rixos Building in Konya, Turkey.

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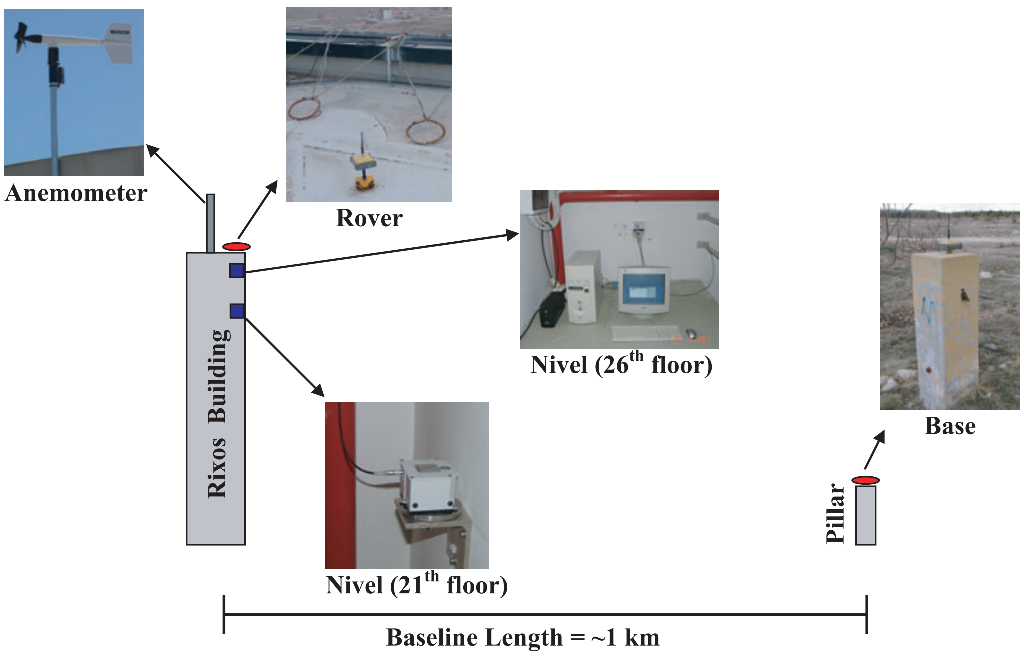

Figure 2: Schematic overview of the GPS, inclinometer and anemometer deployment for the building monitoring.

In addition to GPS and inclination sensors, an anemometer, the Young Model 05103 wind monitor manufactured by the Campbell Scientific, has been installed on the top of the building in order to monitor horizontal wind speed and wind direction. Initial (zero) direction of the anemometer has been oriented along the X direction of the inclination sensors. It can measure wind speed with ± 0.3 m/s accuracy and wind direction with $\pm 3^0$ accuracy.

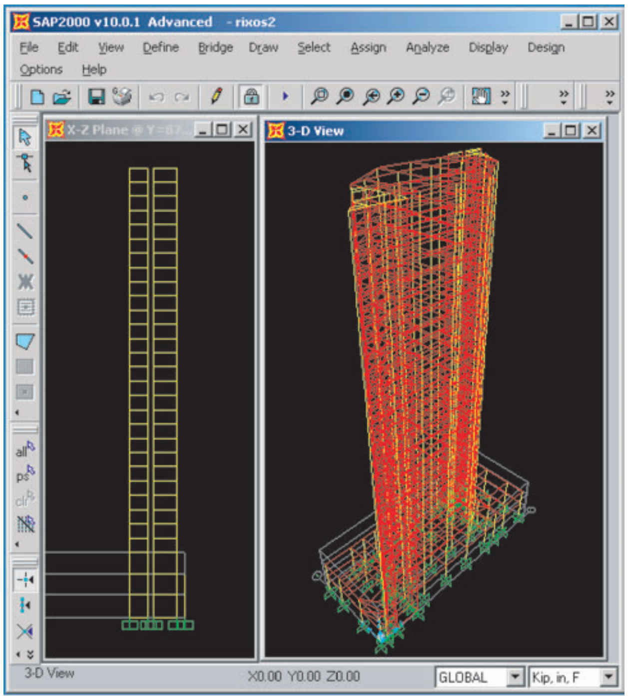

Figure 3: A view of FEM generated by SAP 2000 software.

3. Finite element model (FEM) of the building

The three dimensional model (FEM) of the building was produced using the SAP2000 v10.0.1 structural analysis software, with the aid of the design documents (Figure 3) provided by the structural engineer. The theoretical natural frequencies were predicted using this model (Table 1). In dynamic analyses, normally the first step is the calculation of the natural frequency values. It is usually stated that a small number of modes and the calculation of their frequency values will be sufficient for such studies. The number of modes that will be considered in the anal-

Table 1: FEM predicted natural frequencies and periods.

Mod No.	Frequency (Hz)	Period (sec)
1	0.38	2.6
2	0.55	1.8
3	0.62	1.6

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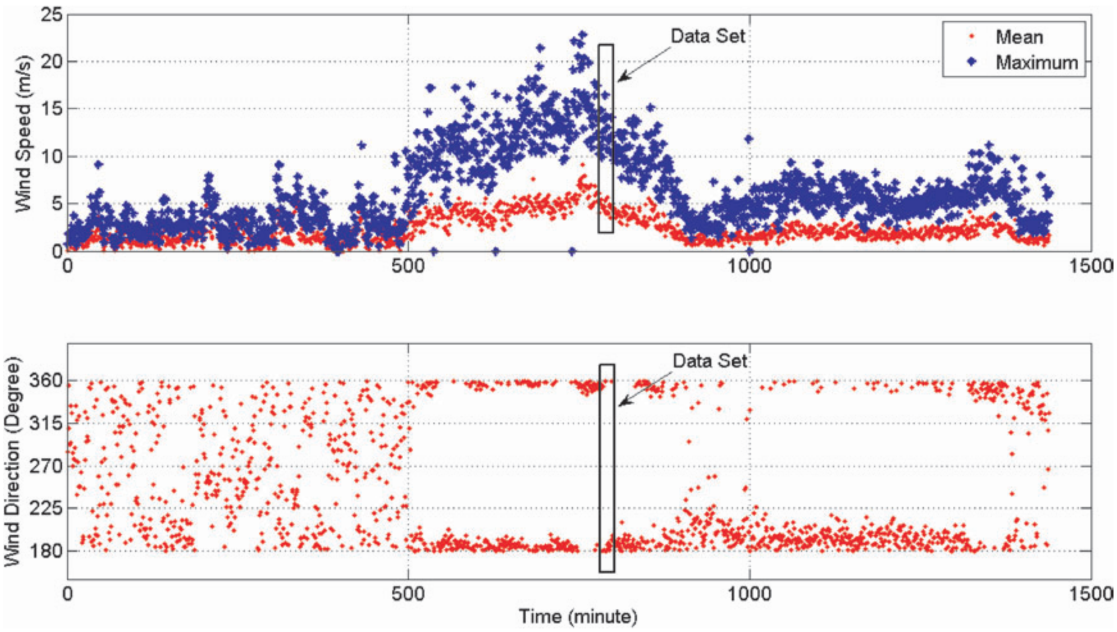

Figure 4: Mean & maximum wind speed (upper), and mean wind direction (bottom) through the day.

yses depends on the type of construction. Since the first mode in tall building analyses involves nearly 90% of the total reaction, the analyses of first three modes becomes sufficient to determine the overall structural behaviour of such buildings.

4. Results and discussions

4.1. *Brief experiment description and wind data*

In this experiment, both GPS and inclination data were collected together on a windy day. The reference GPS receiver was setup up approximately 1 km away, and the GPS sampling rate was 10 Hz. Inclination sampling rate was 1 Hz. The GPS data were collected in kinematic survey mode and post-processed using the Leica Geo Office 3.0 software. One of the Nivel instruments, installed on the 21$^{\text{th}}$ floor, was in operation. However the other Nivel sensor was not available due to an out-of-range problem during this experiment.

Mean and maximum wind speed and the mean wind direction time series from the anemometer are shown in Figure 4. Figure 5 is a zoom-in of the wind data of Figure 4, synchronised with the GPS and inclinometer experiment data set. According to the anemometer recordings, the wind direction was mostly South-West during the experiment, that is, along the X direction of the Nivel (X_{Nivel}), see Figure 9. Furthermore, its maximum wind speed was in the range of 10–16 m/s which was less than 1 km/h.

4.2. *GPS results*

The plots of the 1000 second time series of the kinematic GPS displacements in the X_{GPS} and Y_{GPS} directions are shown in Figure 6. It can be seen that the minimum and maximum displacements in the X direction are around −2.0 cm and 3.0 cm, respectively. For the Y direction, they are approximately −2.0 cm and 2.5 cm, respectively. Is this because of significant static and quasi-static movement of the building under the mean wind loading or because of the multipath effect due to reflecting surfaces on the building? It should be mentioned here that the top of the building contains structural and architectural steelworks near the GPS antenna. Multipath mitigation is not in the scope of this study, for this reason no attempt was made to mitigate multipath error. Short period components (resonant components) of the GPS time series in the X and Y directions are about 6 to 8 mm and 3 to 5 mm, respectively, in amplitude. It can be seen that the resonant components of the GPS measurements in the X direction are larger than in the Y direction.

A key aspect of structural dynamic analysis concerns the behaviour of a structure at resonance. The

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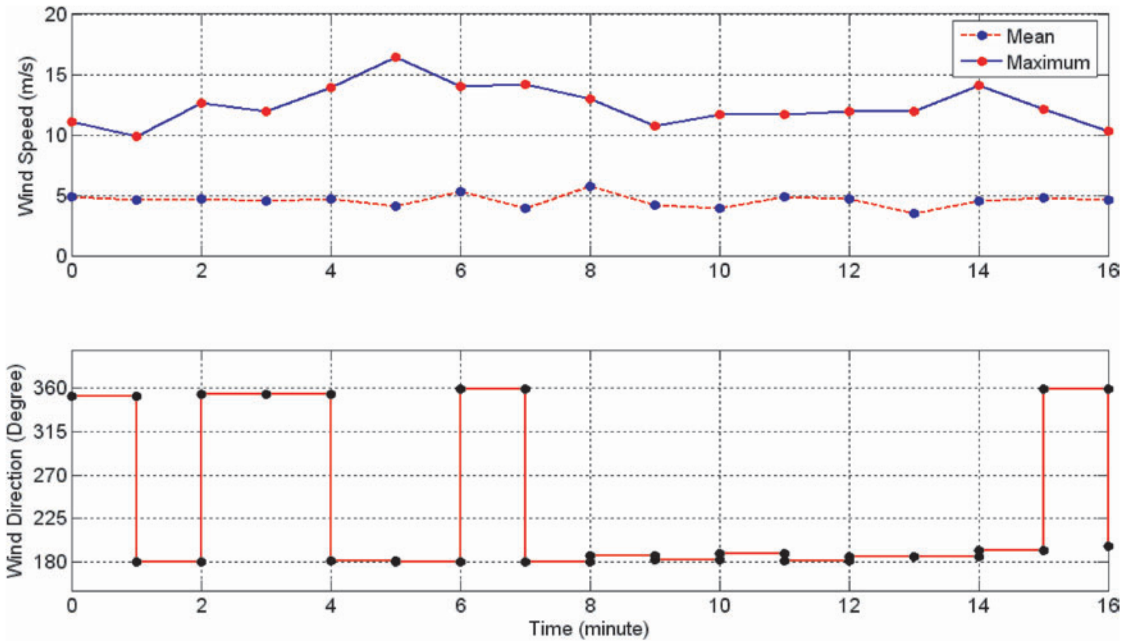

Figure 5: Mean & maximum wind speed (upper) and mean wind direction (bottom) during the experiment.

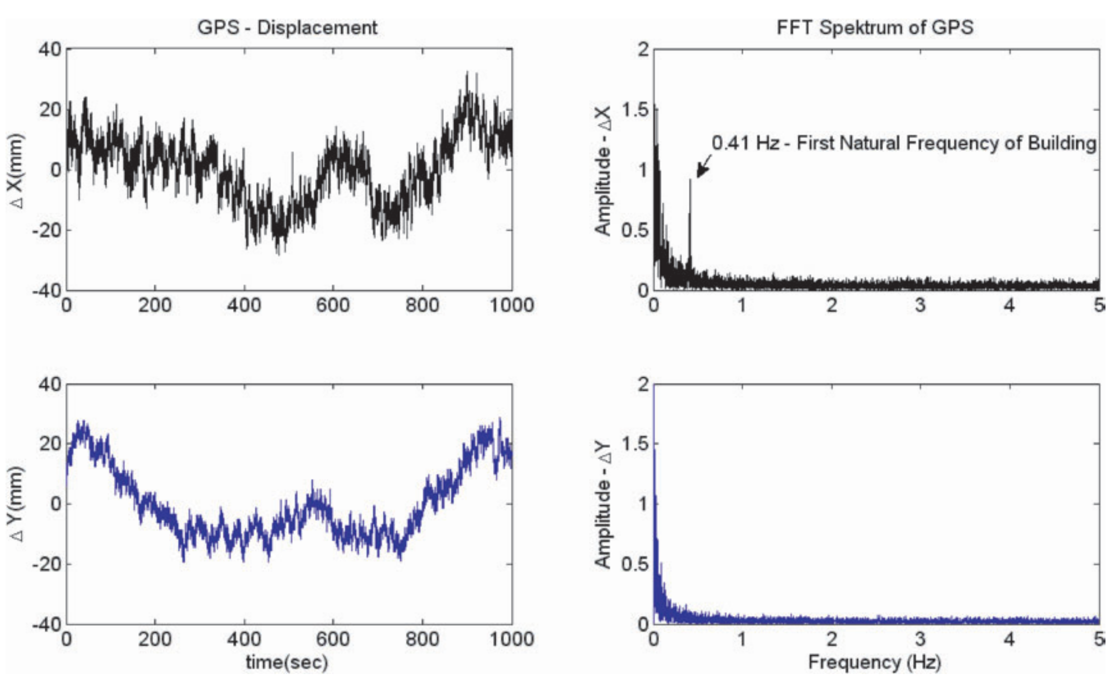

Figure 6: Kinematic GPS displacement time series and FFT spectrum.

natural frequency of vibration of a building corresponds to that structure's resonant frequency. If a structure is subject to vibration at its natural frequency, the displacements of that structure will reach a maximum, i.e. they will be in resonance. The dynamic performance of a tall building under varying loading condition is represented by its natural frequency in the direction of the major and

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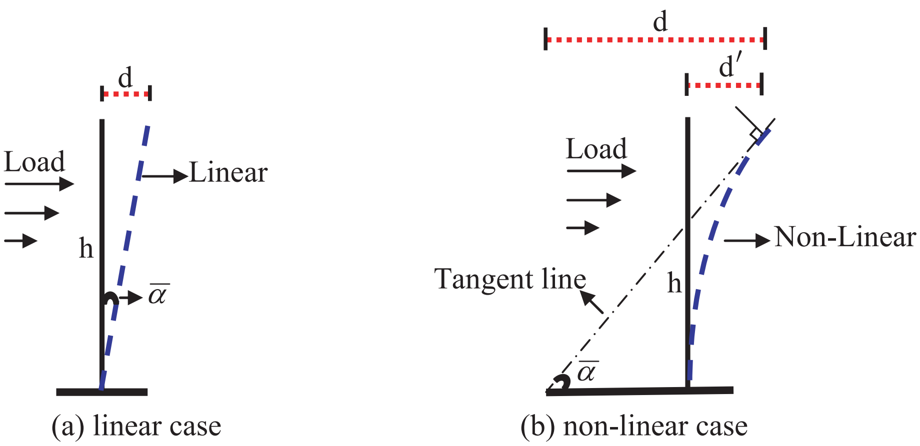

Figure 7: Converting inclination into displacement.

minor axes, and the rotation about the vertical axis. Spectrum analysis via Fast Fourier Transform (FFT) is a common method of converting time domain data into the frequency domain. Thus, the frequency domain signature is obtained using FFT in order to detect the natural frequency of vibration of the building. The FFT spectrum of the GPS data can be seen in Figure 6. It appears to be very noisy at the lower frequency end (0–0.2 Hz) for both the X and Y directions. This is due to multipath error (and possibly other GPS errors) as mentioned before. From the FFT spectrum, it is obvious that there is a 0.41 Hz component in the X direction. There is no significant peak in the Y direction, indicating no movement along this axis. This also indicates that principal axis of the building coincides with this GPS axis.

4.3. *Inclinometer-derived displacement and results*

The Nivel sensor measures small inclination changes of the building. The Nivel sensor measured values are in units of milliradians, i.e. 0.001 rad. Inclination measurements have different units to the GPS measurements. As a result, it is necessary to derive displacement values from the inclination data in order to compare GPS with the Nivel sensor in the time domain. The following equation converts the measured inclination value to a horizontal displacement value:

$$d = h * \bar{\alpha} \qquad (1)$$

where d is the derived displacement in mm, h is the height in metres of the sensor, and $\bar{\alpha}$ is the measured inclination value in mrads. Note that equation (1) is not valid in all cases. It is applicable if a structure maintains its linearity after loading – see Figure 7(a). In the case of a tall building subject to wind loading, for example, the derived displacements from the inclination data using equation (1) may not reflect the actual movement of the building due to non-linear behaviour, due to the accumulated bending effect from each floor of the building, as can be seen from Figure 7(b). Inclinometer-derived displacement time series from equation (1) and its FFT spectrum are given in Figure 8. From the figure it can be seen that the Inclinometer-derived displacement obtained from equation (1) is larger than the resonant component of the kinematic GPS results for both the X and Y directions. The ratio of d to d′ would be an interesting topic for further structural stability model analysis.

The FFT spectrum of inclinometer-derived displacement data appears to be very clean at the lower frequency end (0–0.05 Hz). This indicates that there is no static movement of the building captured by the inclinometer. But a 0.2 Hz centralised cluster signal in both X and Y direction appears to be the quasi-static motion of the building due to wind speed fluctuation. Cross-examination of the FFT results from GPS data analysis are needed to find out how well the inclinometer can detect quasi-static displacements of the building, as well as how close the inclinometer-derived displacement is to the actual displacement. From the FFT spectrum it is obvious that there is a 0.41 Hz component in both the X and Y directions. From the spectrums for both the inclinometer and GPS sensors the dominant frequency is 0.41 Hz, indicating that it is the lowest natural frequency of the building. Note that there is significant

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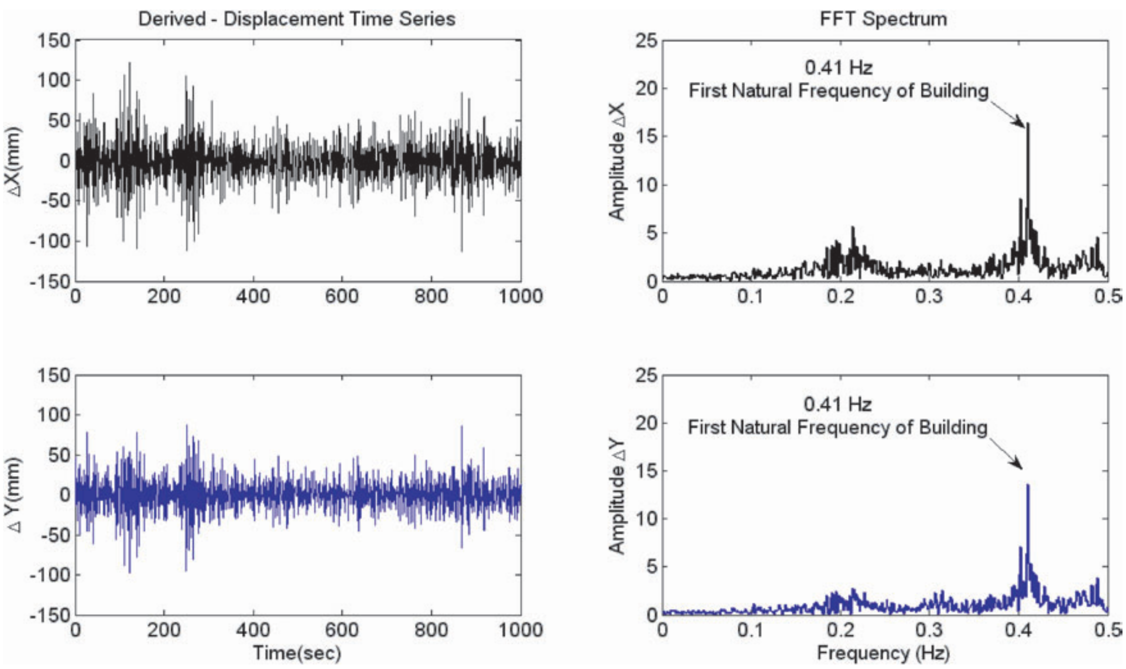

Figure 8: Inclinometer-derived displacement time series and FFT spectrum.

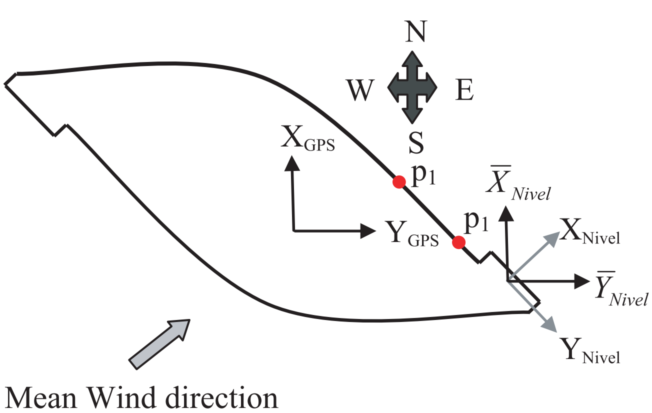

Figure 9: Plan view of the building & GPS and Nivel axes orientation with respect to the building.

peak in the Y_{Nivel} direction, while there is no peak in the Y_{GPS} direction. This is because of the different orientation of the two sensors with respect to the building, see Figure 9.

4.4. *Sensor coordinate systems and transformation*

As can be seen from Figure 9, the Nivel sensor coordinate system and the GPS coordinate axis system are different from each other. For comparison and for integrating the time series from two separate systems, the Nivel coordinates are projected onto the GPS coordinate axis system using the following rotation matrix:

$$\begin{bmatrix} \bar{X}_{Nivel} \\ \bar{Y}_{Nivel} \end{bmatrix} = \begin{bmatrix} \cos\alpha & -\sin\alpha \\ \sin\alpha & \cos\alpha \end{bmatrix} \begin{bmatrix} X_{Nivel} \\ Y_{Nivel} \end{bmatrix} \qquad (2)$$

where α is the angle between the GPS and Nivel coordinate systems, measured and calculated from two adjacent GPS sites on the same building line, along the points p_1 and p_2, parallel to Y_{Nivel}. $\bar{X}_{Nivel}$ and $\bar{Y}_{Nivel}$ are the projected Nivel coordinates onto the GPS coordinate system. After the transformation, note that $\bar{X}_{Nivel}$ and $\bar{Y}_{Nivel}$ are parallel to X_{GPS} and Y_{GPS}, respectively.

The time series and FFT spectrum of the transformed inclinometer-derived displacement data can

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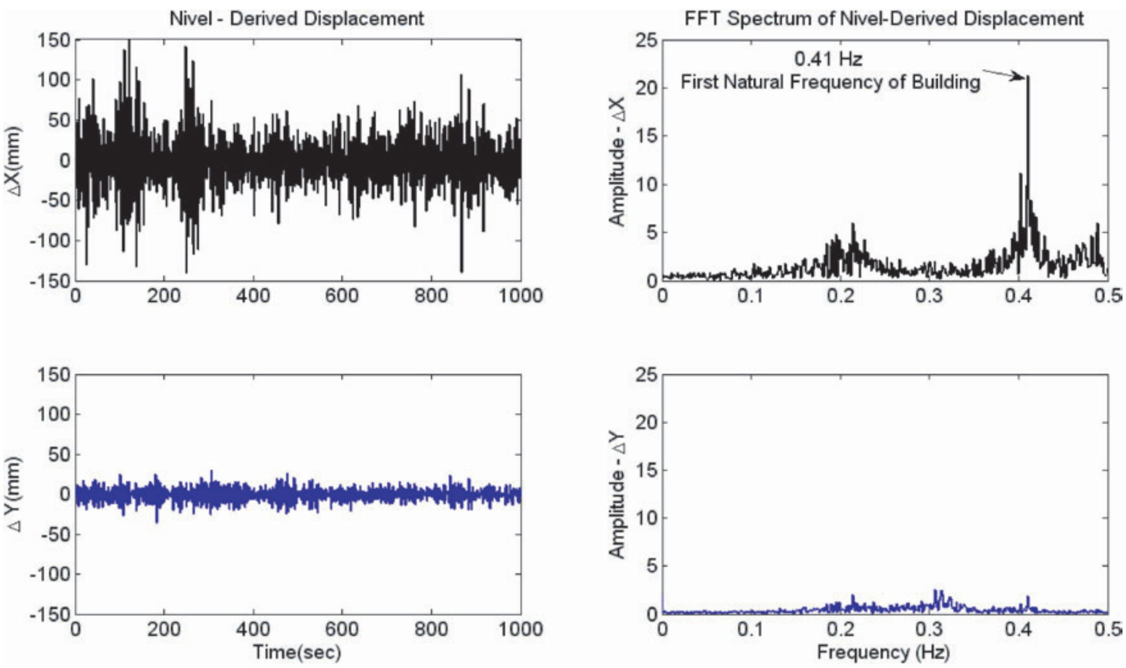

Figure 10: Transformed inclinometer-derived displacements time series and FFT spectrum.

be seen in Figure 10. After transformation, the peak at 0.41 Hz in the Y direction of the Nivel sensor disappears. In terms of the dynamic behaviour of the building along both axes from the two sensor results show a similarity regardless of the magnitude of the displacement and the amplitude of the FFT spectra.

It is clear that the spectra for both the inclinometer and GPS sensors have the dominant frequency of 0.41 Hz, indicating that it is the lowest natural frequency of the building along the X_{GPS} direction. The measured natural frequencies from both sensors also show good agreement (within 7%) with the finite element analysis predictions. The discrepancy between the measured and predicted frequency may be due to unrealistic theoretical assumptions of the model building or considerable changes during the design stage. From the FFT spectrum of both the GPS and inclinometer, it is also obvious that the first mode in the X direction was activated due to wind load, indicating that the building is stiffer in the Y direction than in the X direction.

4.5. *Assessment of dynamic component of GPS and inclinometer using bandpass filtering*

Filtering can be viewed as a procedure for noise removal from a measured process to reveal or enhance information about some quantity of interest. All measured data includes some degree of noise from various sources (Carrion and Spencer 2007). Often classical filters, such as lowpass, bandpass, highpass, or bandreject filters, can be employed to achieve an acceptable result by removing unwanted frequency components of a signal. In order to evaluate and compare the performance of the GPS and inclinometer in terms of measuring the dynamic behaviour of the building, it is necessary to extract the dynamic component using a bandpass filter. A six-order Butterworth bandpass filter with cutoff frequencies of 0.40 and 0.42 Hz was designed and applied to both the GPS and inclinometer data in the X direction. In this experiment the sampling rate and time of both sensors are different. Before applying the filter the GPS data was down-sampled to 1 Hz. After the filtering, the time difference between two systems (GPS time and computer time used for inclinometer) was estimated using cross-correlation and then compensated for. Filtered and synchronised results are depicted in Figure 11.

It can be seen from the figure that the time series envelopes from GPS and inclinometer-derived displacements are almost the same. However, note that the vertical scale of the inclinometer-derived displacement is about 20 times larger in range than the GPS displacement. It can be seen from the figure

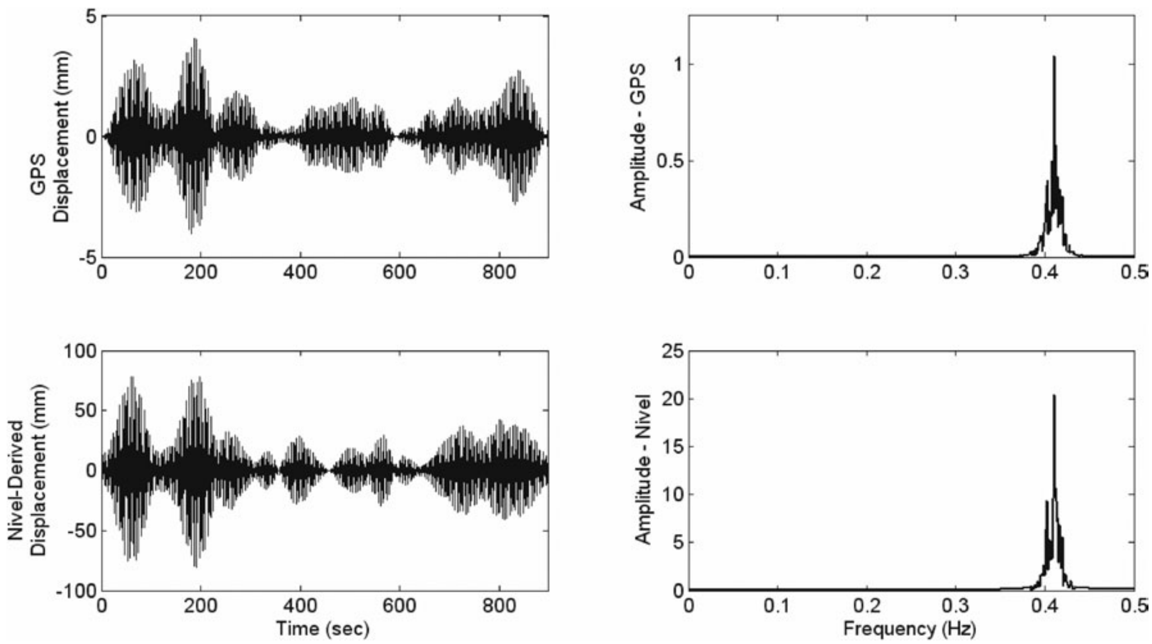

Figure 11: Bandpass filtered time series and FFT spectrum (X direction).

that the amplitude of the FFT spectrum also confirms this scale difference. As mentioned before, this difference is mainly due to the non-linear behaviour of building under wind load. The size of this scale factor not only depends on the height of installed sensor but also the building material and type of loading, e.g. wind or seismic load. In order to derive the actual displacement from the measured inclination data, it is necessary to add a correction factor to equation (1). The correction factor can be determined with the aid of displacement data obtained from GPS or an accelerometer. There is therefore the need for further investigations into this issue with different experimental setups.

5. Conclusions and future work

In this study GPS, inclinometer and anemometer sensors have been installed on a tall reinforced concrete building. The data have been collected during a small-scale wind event, blowing mainly in the South-West direction with a speed lower than 1 km/h. The measured wind-induced response of the building from both sensors has been analysed in both the time and frequency domains for the purpose of measuring the natural frequency of the building, to compare the sensors with each other.

In the frequency domain, both the GPS and inclinometer results show a peak at 0.41 Hz, which is the lowest natural frequency of the building along the X_{GPS} and $\overline{X}_{Nivel}$ directions after transforming the two sensors axes to the same orientation with respect to the building. The measured frequency from the two sensors shows good agreement (within 7%) with the predicted frequency obtained by FEM analysis. In addition, the two sensors agree very well each other in their overlapping frequency range 0–0.5 Hz. In this study, GPS had good performance although the wind speed was low and GPS data had been contaminated by very low frequency multipath error. It can be also be concluded that GPS demonstrated its ability to measure the lowest natural frequency of the building even though the tip displacement is less than 1 cm.

In the time domain, the inclinometer-derived displacement is about 20 times larger than the resonant component of the kinematic GPS. This is mainly due to the non-linear response of the building to wind loading. Therefore it is necessary to add a correction factor to equation (1) in order to derive the actual displacement from the inclinometer measurements. As a result, GPS is still an indispensable tool for measuring the actual tip displacement of the building. However, the inclination sensor can monitor the dynamic response of a tall building during a small-scale and weak wind event, as well as detecting higher frequency modes. Further investigations are still needed to determine the performance of the inclination sensor for monitoring tall reinforced concrete buildings. Thus, future work includes more data collected by GPS and inclinometer sensors with at least 2 Hz sampling rate.

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