Analysıs Of Wınd-Induced Response Of Tall Reınforced Concrete Buıldıng Based On Data Collected By Gps And Precıse Inclınatıon Sensor

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Key words: Wind load, Tall building, GPS and inclination sensor, Full-scale monitoring.

SUMMARY

Wind-induced response of tall buildings consists of three components: static, quasi-static and resonant. It is necessary to use different sensors in an integrated manner – GPS, accelerometer, inclination sensor and so on – in order to monitor and identify these three components. There are some differences among these sensors with respect to data sampling rate, data quality, and their measurands. Therefore, using different sensors together for a monitoring project is important because of the unique contributions of each sensor, as well as the different sensitivities.

Although GPS is capable of measuring absolute displacement directly, multipath effects distort the pseudo-range and the carrier phase observations, and hence decrease the data quality in low frequency range. It is not possible to detect static and quasi-static displacement of structures reliably unless the multipath error is removed by an appropriate mitigation algorithm or procedure. Inclination sensor data may compensate for this weakness of GPS caused by multipath.

In this study, the behaviour of a tall reinforced concrete building (30 stories) under wind load has been monitored by GPS and inclination sensors. 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. According to 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%. This paper also discusses the strengths and weaknesses of GPS vis-a-vis the use of inclination sensors for monitoring the dynamic and quasi-static response of tall buildings under wind load.

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1. INTRODUCTION

Relative displacements are key to assessing structural dynamics. But it is diffucult to measure directly. One of the most popular geotechnical instruments is accelerometer, which is used widely in monitoring the engineering sutructures, such as tall buildigings, towers and suspended bridges. Measuring acceleration response requires a double integration process to derive displacements. For this reason, GPS is a valuable tool to capture actual displacement directly. Lovse et al (1995) studied the performance of the GPS for monitoring tall structures. Celebi et al (1997,1999) discussed the concept and described successful preliminary tests to prove the technical feasibility of the application of GPS to monitoring structures.Tamura et al (2002) reported that RTK-GPS could measure displacements when vibration frequency was less than 2 Hz and the amplitude was more than 2 cm. Numerous studies can be found in published literature on the feasibiliy of using GPS, accelerometer to monitor dynamic structural vibration due to various loading conditions (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 accelerometer for the purpose of monitoring static, quasi-static and dynamic components of engineering structures. Very recently, the application of Robotic Total Station and Terrestrial Laser Scanning for dynamic measurement of displacement has been investigated (Gikas, 2008, 2009).

Many engineering structures, such as tall buildings, towers, cable-suspended bridges, are vulnerable and sensitive to wind-induced vibration and resultant damage. The trend toward constructing higher buildings and longer bridges with less material has contrubuted 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 three most relevant characteristics are shape, stiffness or flexibility, and damping. In addition to the structural characteristics, wind-induced structural vibration also depends on the charecteristics of wind (Liu, 1991). Wind-induced responses of a structure generally consists of three components; static component due to mean wind force, a quasi-static component caused by the low frequency wind force fluctuation and a resonant component caused by the wind force fluctuation near the structure’s first mode natural frequency (Tamura, 2003). For instance, the turbulance in wind buffeting on structures causes vibration. Buffeting can be especially serious if the dominant frequency of turbulance approches the natural frequency of the structure (Liu,1991).

Full-scale measurement is considered to be the most reliable method for evaluating wind effect on and dynamic charecteristic of building and structures. During the last two decades a revolution in data handling and collection has made possible enormous strides in full-scale measurements of dynamic behaviour of tall buildings (Li et al, 2002).

This paper presents the preliminary results of measurement and analysis of a tall reinforced concrete tall building under a small scale wind loading. The full scale measurement were performed with the aid of GPS, inclination sensor and anemometer. The measured wind-induced response of the building from both sensors has been analyzed 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 frequency from the Finite Element Method(FEM). The strengths and weaknesses of GPS vis-a-vis the use of inclination sensors were also discussed for monitoring the dynamic and quasi-static response of tall buildings under a small scale wind loading conditions. The paper ends with some preliminary conclusions.

2. THE STRUCTURE AND ACTUAL DEPLOYMENT

The structure investigated in this study is a 30-storey tall reinforced concrete building in Konya, Turkey. It consists of 44 columns with different sizes and 2 shear-nucleuses (core construction). The building has been used as a hotel owned by Rixos Hotel. The building's structural height is approximately 100 m above the street level. The foundation area of the building is 685 m^2 whose floor plan looks like ellipse (Yigit et al. 2008). The plan view and the picture of the building can bee seen in Figure 1.

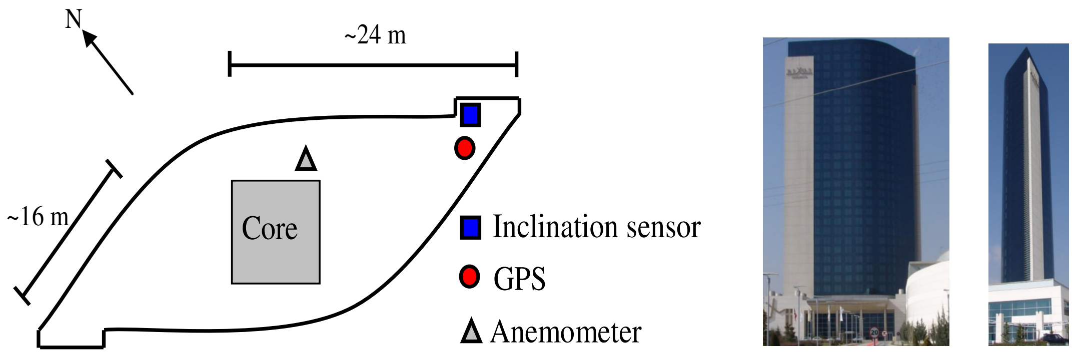

Figure 1. Plan view and Pictures of the Rixos Building in Konya

GPS, inclinometer and anemometer have been deployed on the tall reinforced concrete building in order to monitor its dynamic response to various loading conditions, such as wind and earthquake. Schematic overview of GPS, inclinometer and anemometer sensors array can be seen 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, 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 pillar with good sky view, about 1 km away from the building, as shown in Figure 2.

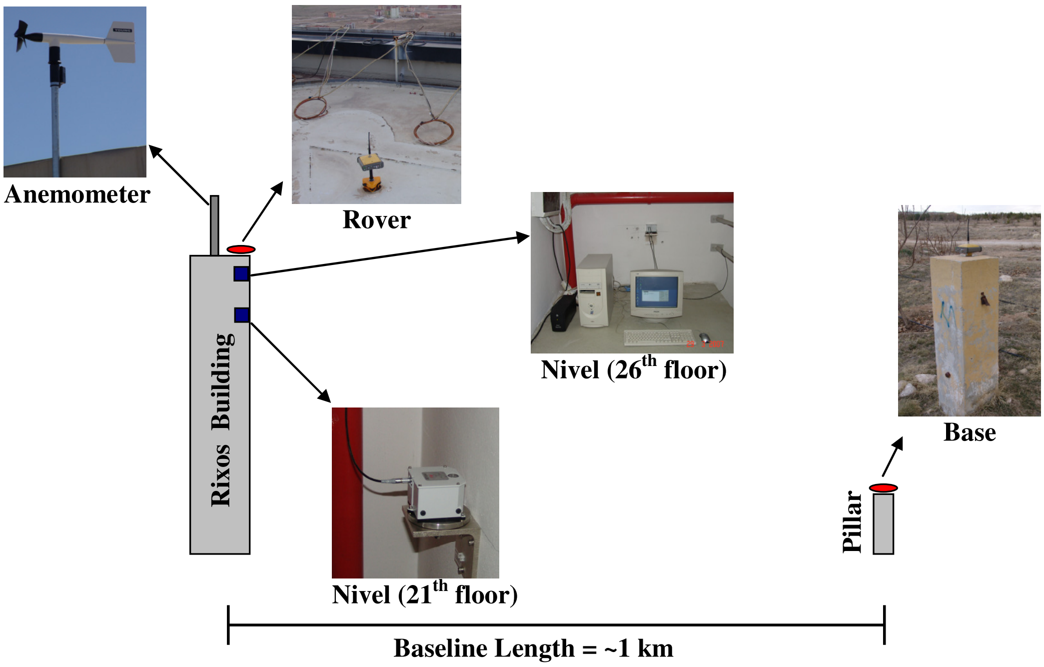

Figure 2. Schematic overview of GPS, inclinometer and anemometer deployment in the building.

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

In addition to GPS and inclination sensors, an anemometer, 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 Y direction of the inclination sensors. It can measure wind speed with ±0.3 m/s accuracy and wind direction with $\pm 3^0$ accuracy.

3. FINITE ELEMENT MODEL OF THE BUILDING

The three dimensional model (FEM) of the building was produced with SAP2000 v10.0.1, structural analysis program, with the aid of the design documents (Fig. 3). The theoretical natural frequencies were predicted by using this model. FEM predicted natural frequencies and period are given in Table 1. In dynamic analyses, normally the first step is the calculation of the natural frequency values. It is usually stated that a few number of modes and the calculation of their frequency values will be practically sufficient for the studies. The number of modes that will be considered in the analyses changes with respect to the type of the construction. Since the first mode in high building analyses involves nearly 90% of the total reaction, the analyses of first three modes becomes sufficient to determine the structural behavior of such buildings.

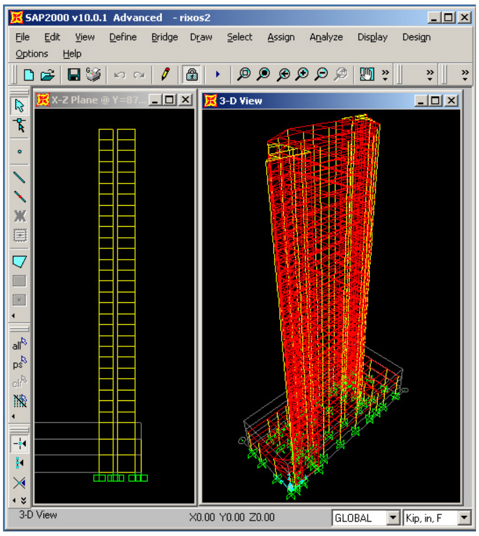

Figure 3. A view of FEM generated by SAP 2000

Table 1 FEM predicted natural frequencies and period

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

4. DATA ANALYSIS AND RESULTS

In this study, both kinematic GPS and inclination data were collected together on a windy day. The reference GPS was setup up 1km away, and GPS sampling rate was 10 Hz. Inclination sampling rate was 1 Hz. We focused on the data part collected by both GPS and inclination sensor to find the natural frequency of the building. GPS data were collected in kinematic survey mode and post-processed with Leica Geo Office 3.0. One of the Nivel data, installed on 21th floor, is available. The other Nivel sensor is not available due to a out of range problem during this experiment, indicating one of the drawbacks of such a geotechnical sensor.

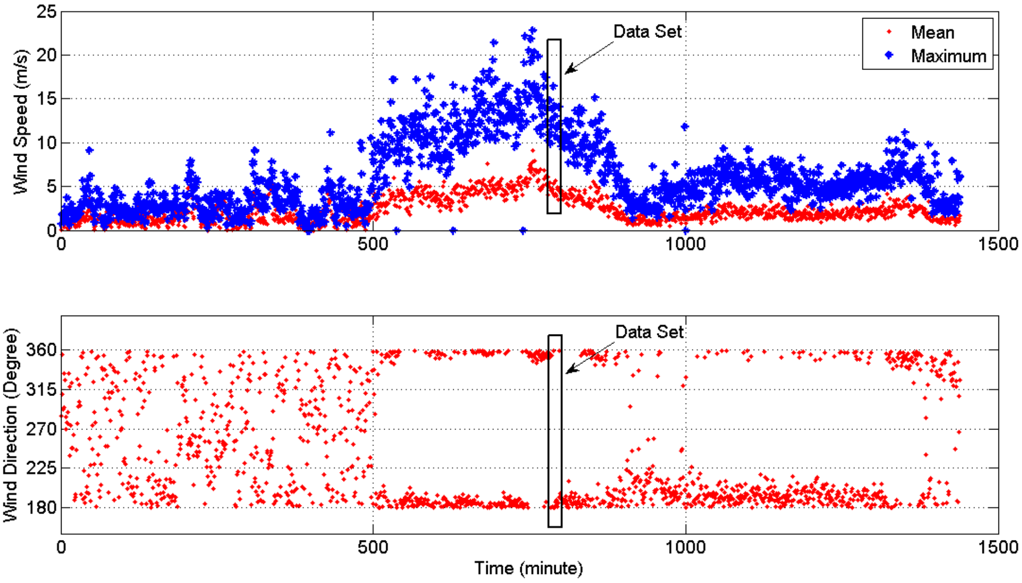

Figure 4. Mean & maximum wind speed (upper) and mean wind direction (bottom) for all day

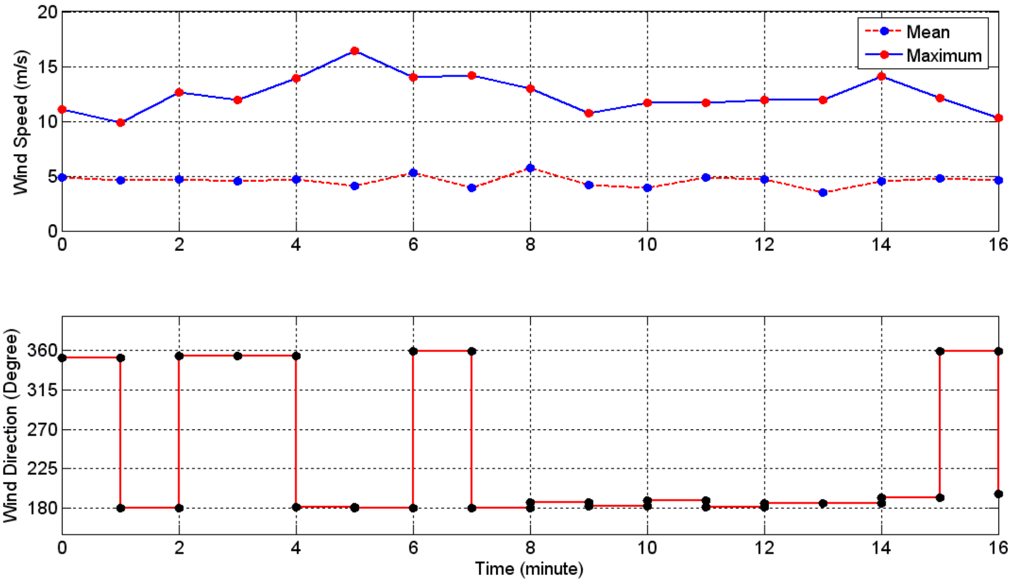

Figure 5. Mean & maximum wind speed (upper) and mean wind direction (bottom) during the experiment

Mean and maximum wind speed and mean wind direction time series from the anemometer can be seen in Figure 4 for all day. Figure 5 is a zoom in of Figure 4, corresponding to the experiment data set. According to anemometer recordings, the wind direction was mostly South-West during the experiment, that is, along the Y direction of the Nivel (Y_{Nivel}), see Figure 6.

The major axes of the building correspond to the axes of the Nivel, see Figure 6. As can be seen from the Figure, Nivel sensor coordinate system and GPS coordinate system axis are different from each other. For comparison and integrating the time series from two seperate systems, GPS coordinates, WGS84, are projected onto UTM grid using LGO, then projected to the Nivel coordinate axis system using the following rotation matrix. 2D transformation equations can be seen below.

$$\begin{bmatrix} \overline{X}_{GPS} \\ \overline{Y}_{GPS} \end{bmatrix} = \begin{bmatrix} \cos\alpha & \sin\alpha \\ -\sin\alpha & \cos\alpha \end{bmatrix} \begin{bmatrix} X_{GPS} \\ Y_{GPS} \end{bmatrix} \qquad (1)$$

Where, α is the angle between the GPS and Nivel coordinate systems, which measured and calculated from two adjacent GPS sites on the same building line paralel to $Y_{Nivel.}$. $\overline{X}_{GPS}$ and $\overline{Y}_{GPS}$ are the projected GPS coordinates to Nivel coordinate system. After the transformation, note that $\overline{X}_{GPS}$ and $\overline{Y}_{GPS}$ are paralel to X_{Nivel} and Y_{Nivel} , respectively.

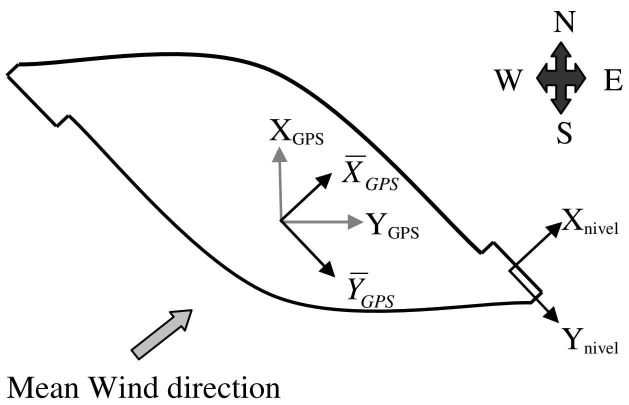

Figure 6. Plan view of the building & GPS and Nivel axes orientation with respect to building

The overall plots of the time series of the kinematic GPS displacements in $\overline{X}_{GPS}$ and $\overline{Y}_{GPS}$ directions are shown in Figure 7. From Figure 7, the minimum and maximum displacements in X direction are around -2.0 cm and 3.0 cm, respectively. For Y direction, they are around -1.0 cm and 1.0 cm, respectively. Is this because of significant static and quasi-static movement of the building under the mean wind loading or because of multipath effect due to reflected surface on the building? It must be mentioned here that the top of the building contains structural and arthitectural stellwork near the antenna. Multipath mitigation is not in the scope of this study. For this reason, no attempt was made to mitigate multipath error. Resonant (dynamic) component of the GPS time series in X and Y direction are around 6 to 8 mm and 3mm to 5mm, respectively. It can be seen clearly that resonant (dynamic) component of the GPS in X direction are larger than in Y direction.

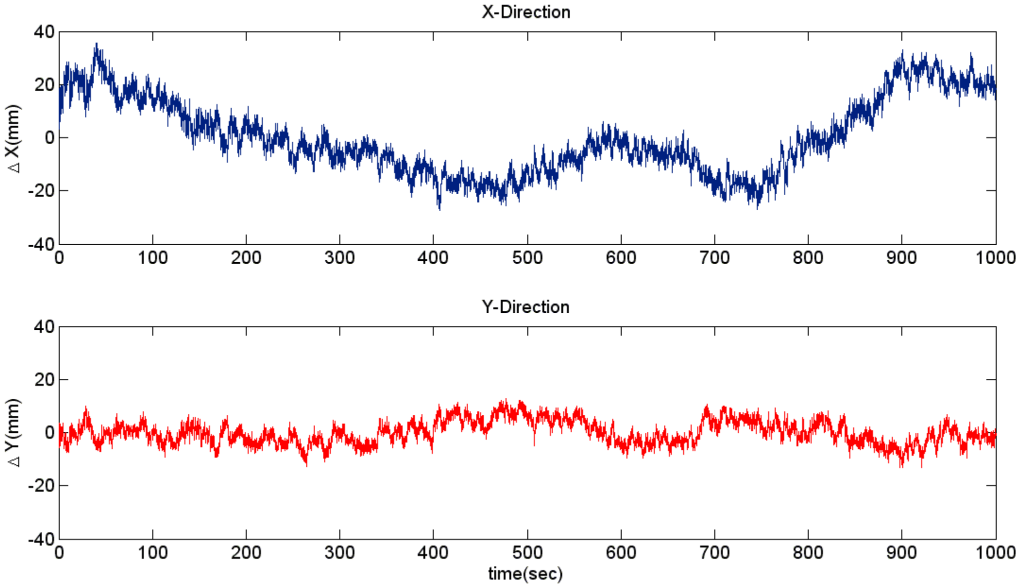

Figure 7. Kinematic GPS displacement time series

The Nivel sensor sense and measure the inclination changes of the building. The Nivel sensor measured values X and Y are in mrad, i.e. 0.001 rad. Inclination measurements have different units to the GPS measurements. As a result, it is necessary to derive displacement value from inclination data in order to compare GPS with Nivel sensor in time domain. The following simple equation can convert the measured inclination value to displacement value.

$$d = h * \overline{\alpha} \quad (2)$$

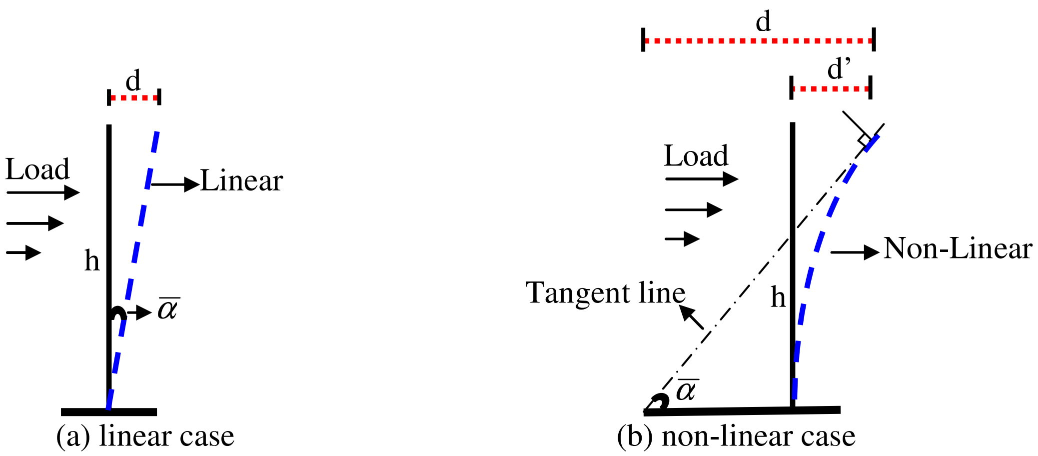

Figure 8. Illusturation of converting inclination into displacement

where, d is the derived displacement in mm, h is the height of the sensor in meter and $\overline{\alpha}$ is the measured inclination value in mrad. Note that the equation 2 is not valid in all cases. It is applicable if a structure keep its linearity after loading, see Fig. 8(a). In the case of tall building subject to wind loading, for example, the derived displacements from the inclination data using equation 2 can not reflect the actual movement of the building due to non-linear behaviour as can be seen from Figure 8(b). Nivel-derived displacement time series from equation 2 are given in Figure 10. From the figure it can be seen that the Nivel-derived displacement is about ten times larger than the resonant component of the kinematic GPS for both X and Y direction. This also supports the above disscussion. Hovewer, it is obvious that X direction of the Nivel is larger than Y direction, which is similar to corresponding GPS axes. This clearly indicate that two sensor show similarity in terms of monitoring and sensing the movement direction of the building.

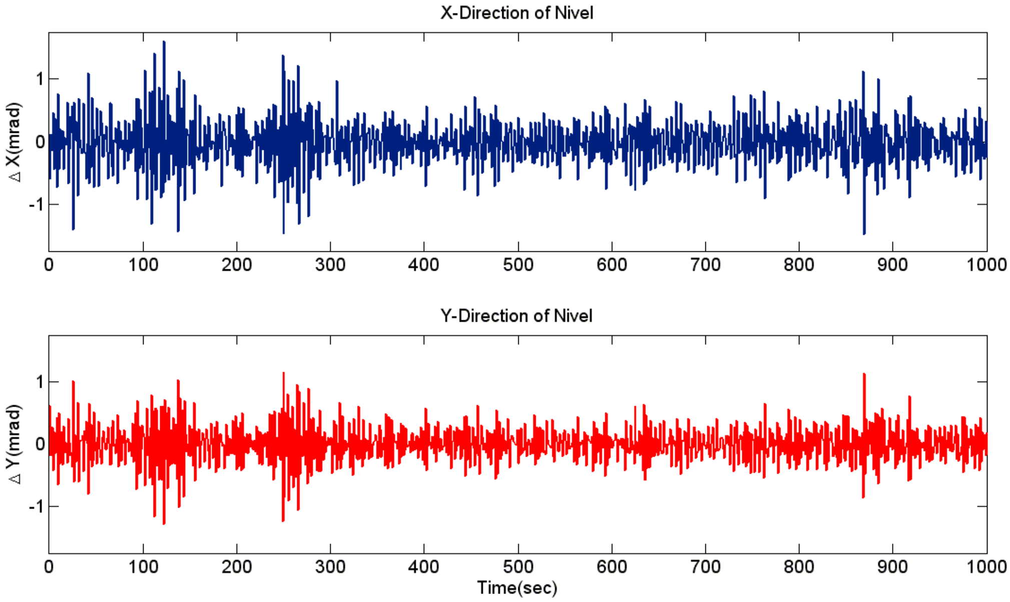

Figure 9. Inclination time series

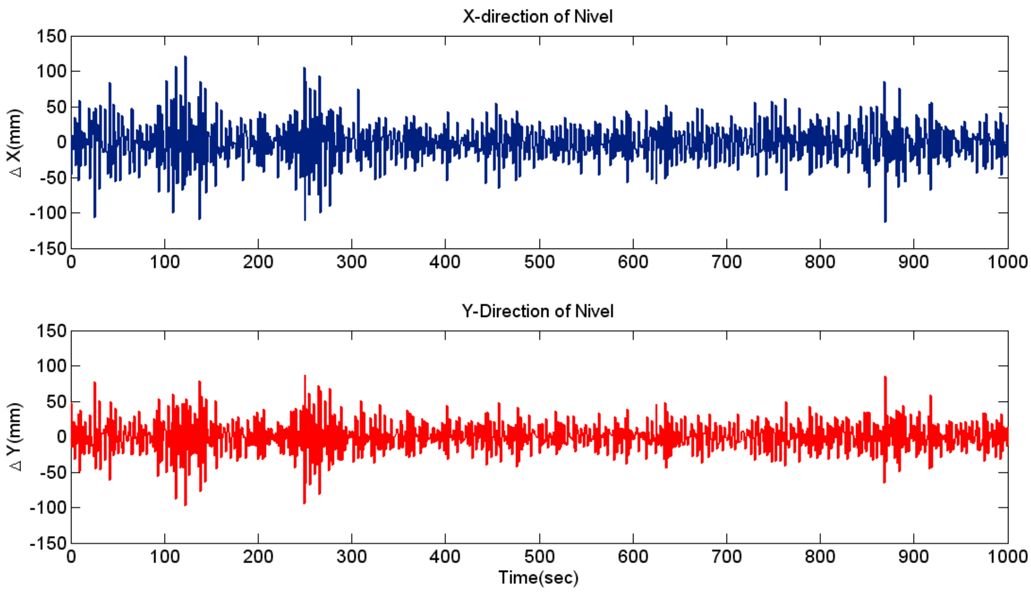

Figure 10. Inclinometer-derived displacements time series

A key aspect of structural dynamic analysis concerns the behavior of a structure at resonance. The natural frequency of vibration of a structure 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. resonance. The dynamic performances of tall building under varying loading condition are represented by its natural frequency in the direction of major, minor axes and rotation around vertical axis. Spectrum analysis through Fast Fourier Transform (FFT) is a common method of coverting time domain data into its frequency domain. Thus, frequency domain signature is obtained using FFT in order to detect natural frequency of vibration of the building. Figure 11 is the FFT spectrum of GPS data. Figure12 is a zoom-in of the overall GPS spectrum shown in Figure11. It appears to be very noisy at the lower frequency end (0-0.2 Hz) for both X and Y direction. This is due to multipath error and other GPS error as mentioned before. From Figure 12, it is obvious that there is a 0.41 Hz component in both X and Y direction.

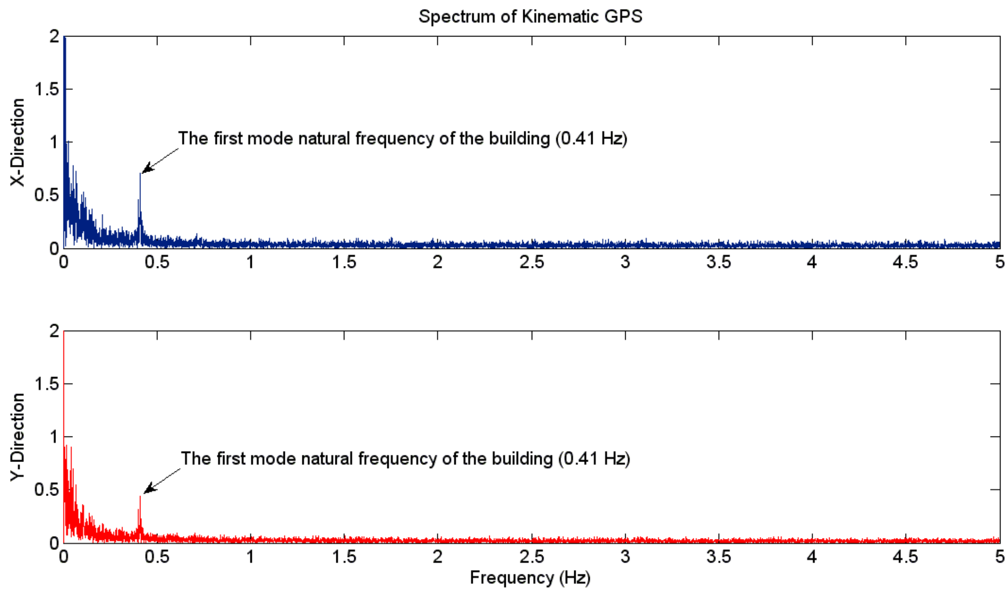

Figure 11. FFT Spectrums of Kinematic GPS Time Series for X & Y directions

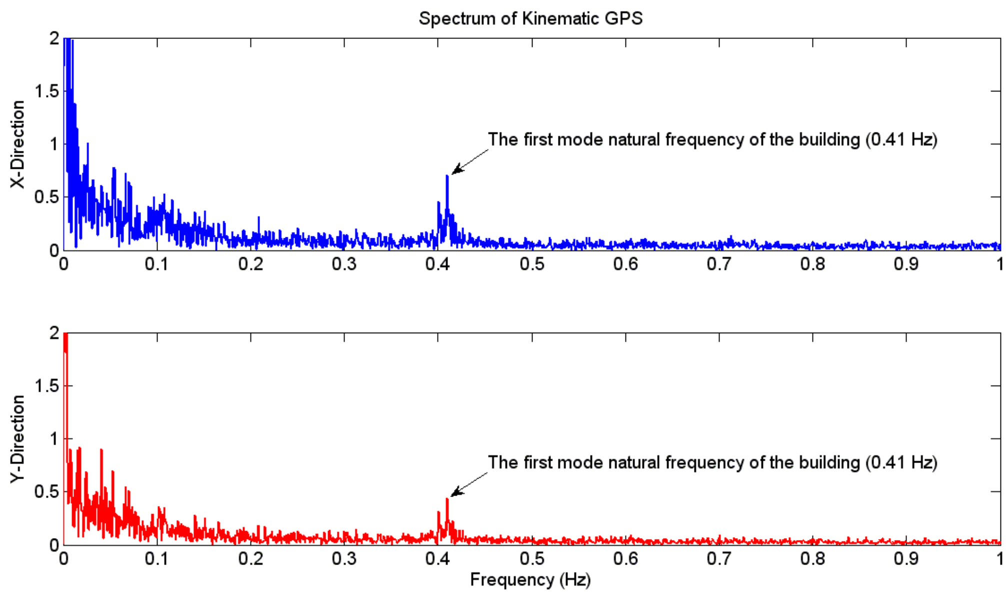

Figure 12. Zoom in of the FFT Spectrums of Kinematic GPS Time Series

Figure 13 is the FFT spectrum of Nivel-derived displacement data. Inclinometer data in Figure 13 appear to be very clean at the lower frequency end (0-0.05Hz). This indicates that there is no quasi-static or static movement of the building due to nature and structure of the wind during the event. This result also proves that the GPS data were strongly contaminated by multipath error. Further experiments are needed to find out how well inclinometer can detect quasi-static and static displacements of the building due to mean wind loading, as well as how close inclinometer-derived displacement is to the actual displacement.

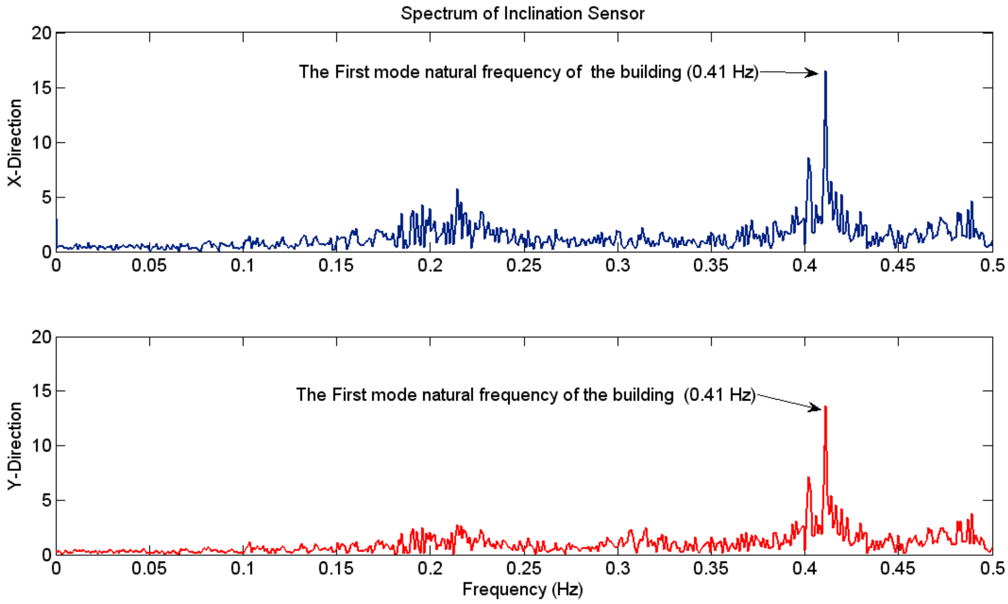

Figure 13. FFT Spectrum of Inclinometer Derived displacement time series

It is clear that the spectrums 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. The measured natural frequencies from both sensors also showed good agreement (within 7%) with finite element analysis predictions. The discrepancy between the measured and predicted frequency may due to unrealistic theoretical assumptions of the model building or considerable changes during the design stage, for example. From the FFT spectrum of both GPS and inclinometer, It is also obvious that the amplitudes of first mode in the X direction are stronger than in the Y direction, indicating that the the Y direction of the building is stiffer than the X direction of the building. it also is because of the Y direction of the building has a thick length than the X direction.

5. CONCLUSION AND SUGGESTIONS

In this study, GPS, inclinometer and anemometer have been installed on a tall reinforced concrete building. The data have been collected during a small scale wind event, mostly in the South-West direction. The measured wind-induced response of the building from both sensors has been analyzed in both the time and frequency domains for the purpose of detecting natural frequency of the building and comparing the sensors with each other as well as comparing the measured frequency with the predicted frequency obtained from FEM.

In the frequency domain, both the GPS and inclinometer show a peak at 0.41 Hz, indicating the lowest natural frequency of the building. The measured frequency from the two sensors showed good agreement (within 7%) with the predicted frequency obtained by FEM. In addition, the two sensors agree very well each other in their overlapping range 0 – 0.5 Hz. In this study, GPS show good performance although the wind speed was low and GPS data have been contaminated by multipath error. It can be also said that GPS proved its ability of capturing the lowest natural frequency of the building although tip displacement is less than 1 cm.

In the time domain, the Nivel-derived displacement using equation 2 is about ten times larger than the resonant component of the kinematic GPS for both X and Y direction. This is likely due to the non-linear behaviour of the building response to wind loading. As a result, GPS is still indispensable tool in order to detect actual tip displacement of the building. However, inclination sensor can monitor dynamic response of a tall RF building during a small scale and weak wind event. Therefore, inclination sensor is a good tool to monitor dynamic response of a tall RF building under weak wind loading condition. Further investigations are still needed to find out the performance of the inclination sensor in monitoring tall RF buildings.

ACKNOWLEDGMENTS

The first author is supported to perform his Ph.D. research in the School of Surveying and Spatial Information Systems, Faculty of Engineering, The University of New South Wales for 12 months by an International Research Fellowship Programme provided by the Scientific and Technological Research Council of Turkey. His Ph.D. and this study are also funded by the Scientific Research Projects Grant of Selcuk University. In addition, the authors would like to thank the managers of the Konya Rixos Hotel for allowing access to the structure.

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