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MONITORING OF TALL BUILDING'S DYNAMIC BEHAVIOUR USING PRECISION INCLINATION SENSORS

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Abstract: The observations made on the engineering structures like dams, bridges, viaducts and high buildings provide to determine whether the structure was built in accordance with the project or not and whether it behaves reliably or not. In the light of this information, new information that should be considered in the assumptions used in the project can be obtained and some parameters can change. The dynamic parameters like wind, temperature, earthquake loads especially acting on the tall buildings cause the structure move in the horizontal direction.

A high precision inclination sensor, a GPS site and an anemometer were installed in order to observe the dynamic behaviors of the 30-storey high Rixos Hotel building in the horizontal direction. The floors of the building are formed from a lobby, a clerestory, 4 basement floors, an equipment floor and 26 floors with hotel rooms. The biaxial inclination sensors namely Leica Nivel 220 were installed at the 21st and 26th floors on one of the shear-nucleus. The GPS site was located at a place on the roof from which the satellite view would be maximum and the behavior of the building would be reflected at best, and the Young Anemometer was installed at a most dominating place on the roof in order to measure the velocity and the direction of the wind. The horizontal movements of the building, the velocity and the direction of the wind are still continuously observed using the biaxial inclination sensor and the anemometer.

In this paper, there were given information about the installation plan of inclination sensor, anemometer and GPS point that were installed to determine the dynamic behaviors of the building. We dealt with monitoring strategy of tall building by using inclination sensor and GPS, the data-acquisition periods, comparison of two monitoring system and the purposes of the study. In addition, we explained system and system identification procedure related to deformation monitoring.

1. INTRODUCTION

In recent years, a notable increase in constructing large structures such as tall buildings and long span bridges has come into existence which were designed by using the principles of both material and structural mechanics. Monitoring the performance of full-scale structures by reliable systems and using integrated geodetic and geotechnical instrument, such as GPS and accelerometer became more popular with every passing day. In order to obtain valuable information about the structures, there are some fundamental stages in structural monitoring, such as installation, data acquisition, analysis and interpretation. The first stage in monitoring is the selection and installation of instrument(s) and sensor(s) in accordance with the aims planned to achieve at the end of the study. Sensors used for monitoring the deformations consists of especially the geodetic sensors such as GPS, motorised theodolite etc., the geotechnical sensors such as accelerometer, extensometer, tiltmeter, inclinometer etc., and the meteorological sensors such as anemometer and temperature sensors. The installation of the selected sensors on the structures is extremely important to obtain the exact data sequences under different loading conditions. Data-acquisition strategy is closely related to the analysis and interpretation stage after which the accurate and reliable conclusion and interpretation with respect to the analysis results will be performed by the help of the experienced civil engineers in structural monitoring.

So far, there were many various studies on structural monitoring in geodetic engineering literature (Lovse et al. 1995, Ogaja et al. 2003, Li et al. 2006, Li et al. 2006, Brownjohn 2004, Çelebi et al. 2002, Roberts et al. 2004, Hristopulos et al. 2006 Barnes et al. 2004, Roberts et al. 2000) whose number increases in parallel with the data-acquisiton capability of sensors, the usability and efficiency of different signal processing and the time series analysis techniques.

In this study, the tall structure will be considered as a system. The inputs of this system are wind speed, wind direction and temperature. The outputs of this system are X and Y direction movement of building. The inputs will be measured by an anemometer and a temperature sensor, respectively. The outputs will be measured by inclination sensor and GPS, seperately. Therefore, a high precision inclination sensor, a GPS site point and an anemometer were installed on the Rixos Hotel building in Konya in order to observe the dynamic behaviors of the building in the horizontal direction. The floors of the building consists of a lobby, a clerestory, basement floors, an equipment floor and 26 floors with hotel rooms. The biaxial inclination sensors namely Leica Nivel 220 were installed at the 21st and 26th floors of the building on one of the shear-nucleus. The GPS site was located at a place on the roof from which the satellite view would be maximum and the behavior of the building would be reflected at best, and the Young Anemometer was installed at a most dominating place on the roof in order to measure the velocity and the direction of the wind. The horizontal movements of the building, the velocity and the direction of the wind are still continuously observed using the biaxial inclination sensor and the anemometer, respectively.

2. SYSTEM AND SYSTEM IDENTIFICATION PROCEDURE

A *system* is an object in which variables of different kinds interact and produce observable signals. The observable signals that are of interest to us are usually called as *outputs*. External signals that can be manipulated by the observer are called as *inputs*. Others are called *disturbances* and can be divided into those that are directly measured and those that are only observed through their influence on the output(Figure 1). The distinction between inputs and measured disturbances is often less important for the modeling purpose(Ljung 1999).

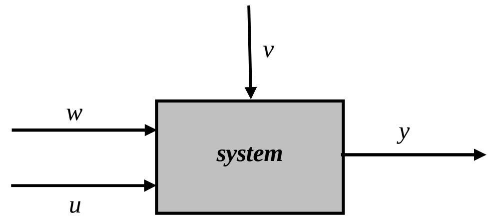


Figure 1 - A system with output y, input u, measured disturbance w, and unmeasured disturbance v

In system theory, the set-up an appropriate mathematical-physical representation of the transfer function of a dynamic system is called system identification(Welsch and Heunecke 2001). System identification deals with the problem of building mathematical models of dynamical systems based on observed data from the system. The identification problem derives the transfer function from the observed input and output signals (Ljung 1999).

One could build a so-called *white-box model* based on first principles, eg. a model for a physical process from the Newton equations, but in many cases such models will be overly complex and possibly even impossible to obtain in reasonable time due to the complex nature of many systems and processes.

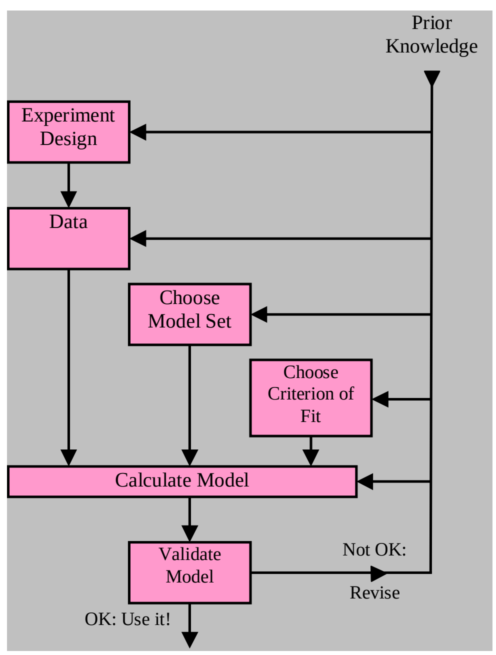


Figure 2 - The System Identification Loop(Ljung 1999)

A much more common approach is therefore to start from measurements of the behavior of the system and the external influences (inputs to the system) and try to determine a mathematical relation between them without going into the details of what is actually happening inside the system. This approach is called system identification. Two types of models are common in the field of system identification (Wikipedia 2008):

- *Grey box model:* although the peculiarities of what is going on inside the system are not entirely known, a certain model is already available. This model does however still have a number of unknown free parameters which can be estimated using system identification. This is also known as semi-physical modeling. [1]
- *Black box model:* No prior model is available. Most system identification algorithms are of this type.

System identification can be done in either the time or frequency domain. The system identification procedure has a natual logical flow: first collect data, then choose a model set, then pick the 'best' model in this set. System identification loop can be seen in Figure 2.

3. SENSORS USED IN THIS STUDY AND ITS INSTALLATIONS

3.1. Basic Properties of the Structure

The structure used in this study was a 30-storey high reinforced concrete building in Konya which consists of 44 columns with different sizes and 2 shear-nucleuses (core construction). The building was used as a hotel by Rixos Hotel Konya. The building's structural height is approximately 100 m. The foundation area of the building is 685 m^2 whose floor plan is ellipse. Having a dynamic design, the sizes of the building are 20 m in the west-east and 52 m in the north-south directions (Figure 3).

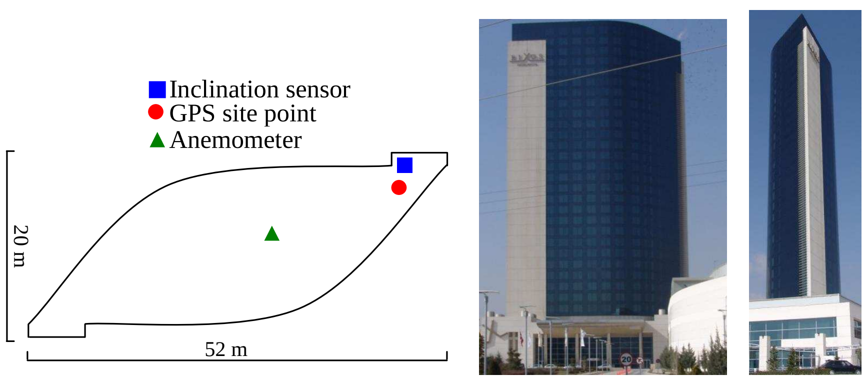


Figure 3 - Top, front and side views of the building

3.2. Sensors and its installations

3.2.1. Inclination Sensors

Inclination sensors are good tools to monitor the instant and continuous inclination changes of the structures to identify deformations occuring on the body of the structures. Leica Nivel 220 by Leica Geosystems is a very precise inclination sensor that is able to sense the inclination changes in two different directions perpendicular each other. The sensor has its own coordinate system, which is defined regarding the origin. Therefore, inclinations measured are based on two axes, X and Y. The sensor's working range is ±1.5 mrad(mm/m). The sensor measures also the temperature of the environment to eliminate the errors occured due to temperature changes(Anonym 2007).

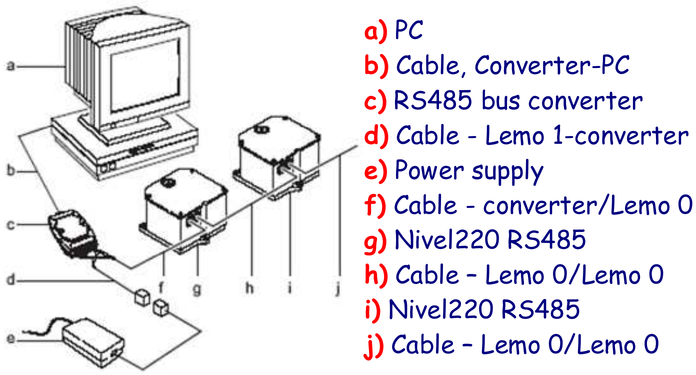


Figure 4 - Configuration of a Nivel 220

Nivel 220 inclination sensor works with an optoelktronic principle that has no moving part. The reference plane is provided by a fluid horizontal that is always perpendicular to the plumb line direction. The inclination is measured with the difference of an angle between true horizon and the surface of an object on where the sensor placed. The sensor components can be seen in Figure 5.

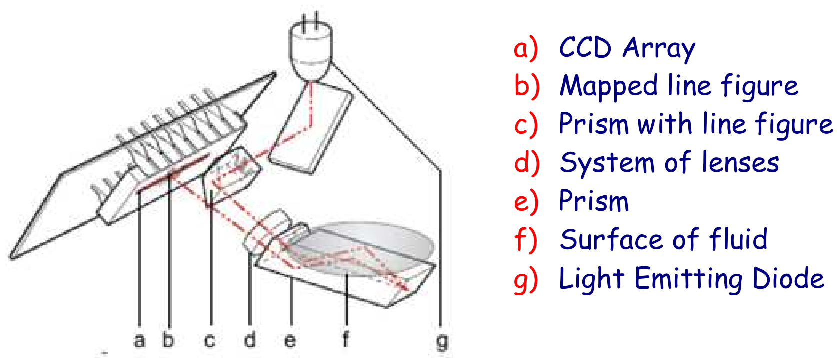


Figure 5 - Sensor components

Principle operating is as follows

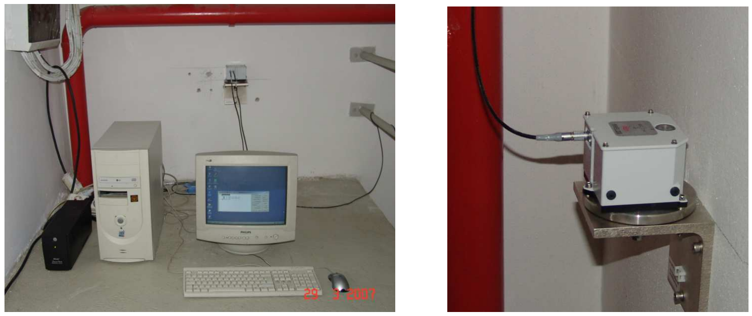
- The line figure (c) is located on a prism.
- This line figure is illuminated with a **L**ight **E**mitted **D**iode (g).
- The system of lenses (d) projects the illuminated line figure (c) through a prism (e) and the fluid surface (f) onto the CCD-array (a).

Specifications of Nivel 220 sensor can be seen in Table 1.

Measuring Range	-1.5 to +1.5 mrad
Resolution	0.001 mrad (mm/m)
Zero-point stability	0.00471 mrad / ^{o}C
Accuracy	± 0.0047 mrad
Temperature sensor measuring range	-20 to +50 ^{o}C

Table 1 - Specification of Nivel 220 Sensor

In this study, the biaxial inclination sensors namely Leica Nivel 220 were installed at the 21st and 26th floors on one of the shear-nucleus (Figure 6).



26th Floor 21st Floor

Figure 6 - Installed inclination sensors and its monitoring system

For example, the inclination sensor data collected in 23rd March 2006 during one day can be seen in Figure 7. That day was windy from 09:00 to 18:00.

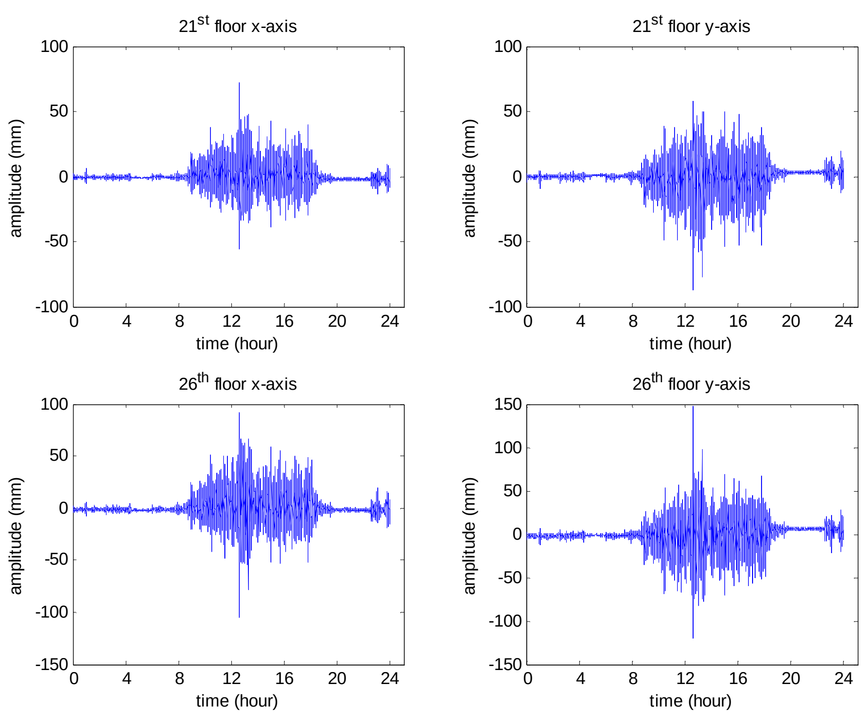
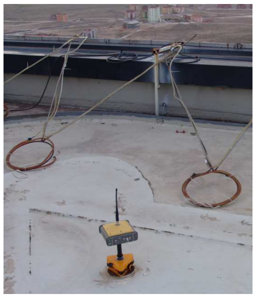


Figure 7 - Inclination sensor data collected in 23rd March 2006 during one day

3.2.2. GPS Sensors

A GPS site point was installed at the north-east corner of the top of the building. GPS system consisted of two Topcon HiPer Pro receivers, one installed as a rover station on the Rixos Hotel rooftop, as shown in Figure 8(a), and the other as a base station on pillar with good sky view, about 1000 m from Rixos Hotel, as shown in Figure 8(b). Topcon Hyper Pro is a dual-frequency, GPS+ receiver.



(a)

(b)

Figure 8 - (a) Rover station (b) Base station

3.2.3. Anemometer

In this study, the anemometer was installed at top of the building, as shown in Figure 9. Initial direction of the anemometer was chosen as the same of the X direction of the inclination sensors. Wind velocity and wind direction data were recorded at one minute sampling rate by using Young Model 05103 anemometer. This anemometer can measure wind speed with ±0.3 m/s accuracy and wind direction with $\pm3^0$ accuracy.

Figure 9 - Young Model 05103 Anemometer at top of the building

The content of the file recorded by the anemometer consists of month, day, hour, minute, average wind speed, maximum wind speed, average wind direction and standard deviation of wind direction.

4. DATA GATHERING STRATEGIES AND PLAN

Monitoring process and strategy were determined according to our main purpose which is to find transfer function between wind speed and direction and building response, between temperature change and building response. Thus, the building will be monitored continuously by inclination sensors for one year period and several times by GPS under windy weather conditions. Data- gathering plan and monitoring plan can be seen in Table 2. In addition, the monitoring plan is illustrated in Figure 10.

	Data-gathering strategy	Data-sampling interval	Collecting data
Anemometer	Continuously(one year)	60 sec.	Wind Speed Wind Direction
Inclination Sensor	Continuously(one year)	1.5 sec.	Inclination changes of X and Y direction
Kinematic GPS	Different Windy Weather Condition(several times)	0.1 sec.	Coordinate changes of X and Y direction

Table 2 - Data-gathering plan

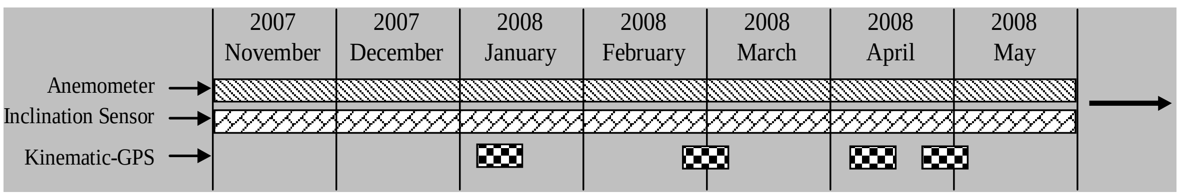


Figure 10 - Monitoring plan

5. OBJECTIVES AND EXPECTATIONS

The objectives and expectations at the end of the this study are listed in the following.

- To monitor the long term and the short term dynamic behaviors of the tall buildings using inclination sensor and GPS under various and different loading conditions.
- To study and analyze the GPS and the inclination sensor data collected in both time and frequency domains using digital signal process and digital filtering techniques.
- To determine the mathematical relationship between loads and the structural responses.
- To find the transfer function between wind speed, wind direction and building's vibration frequency by using system identification procedure.
- To find out the structural behaviors under changing seasonal temperatures by using system identification procedure.
- To compare the strengths and the weaknesses of the GPS and the inclination sensor.
- To evaluate the performance and efficiency of the inclination sensor at long term and short term monitoring of dynamic behaviors of the tall structures.
- It will be determined whether the behavior of the building under wind loading is in harmony with the project or not.
- The variation of some parameters required in the new project designs will be provided according to the analysis results.
- It will be possible to compare the present dynamic behaviors of the building with the dynamic behaviors before and after disasters like earthquake, flood, etc. whether they have similar properties or not. Thus, the risk analysis of the building will also be possible.

6. CONCLUSIONS

In this paper, there were given information about (1) the monitoring of tall building's responses under different loads such as wind loading, earthquake loading and temperature change, by using high precision inclination sensors and GPS sensors, (2) the inclination sensors and their functioning principles, (3) the installation of inclination sensors, GPS points and anemometer on the building of nearly 100 m high, (4) the data-acquisition strategy, (5) the purpose of this study and (6)the system identification.

Monitoring process and its strategy were determined in accordance with the main purpose of our study, i.e. determining the transfer function of wind speed & direction versus the response of the building. The engineering structures like tall buildings should be monitored at different dates with different wind loading conditions in order to obtain the accurate system behaviours of them which will be directly related to the quality and the selection of the data set used for the system identification procedure.

The forthcoming studies about the subject of this study is planned to be about the selection of the most proper data sets, the analyses of these data sets using signal processes and time series analyses, the determination of the transfer function of wind speed & direction with the response of the building by using the system identification procedure. Additionally, after analyzing the data gathered in this study, the strength and weakness of the inclination sensors in monitoring the reactions of the tall buildings under various loading conditions will be also taken into consideration in the future studies.

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