A CONCEPT FOR MONITORING WIND ENERGY TURBINES WITH GEODETIC TECHNIQUES

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Abstract: The presented paper deals with the development of a monitoring concept for a wind energy turbine with conventional geodetic sensors like GPS receiver, tacheometers and inclinometers as well as comparably new sensors like terrestrial laser scanners. As an example of use, two wind energy plants in Schliekum and Göhl (Germany) were chosen to implement the monitoring concept with the mentioned sensors.

1. Introduction

The energy production through wind energy turbines is a fast growing market. Because of the fact that a large number of wind energy turbines (WET) have been built up to now monitoring techniques are required to guarantee the stability and longevity of these objects.

Figure 1: WET in Schliekum, Germany

The WET in Schliekum is of type Tacke 1.5 S and has an overall pylon height of 77 m (Figure 1). The conical steel pylon was built on a concrete base and consists of 3 segments with heights of 25.9 m, 25.9 m and 25.0 m which are joint with circular flange connections. The steel thickness starts with 22 mm at the bottom and decreases to 8 mm at the top. To optimize the power output, the turbine can operate at speed levels of 12, 18 and 21 rotations per minute (RPM). Continuous operation with rotation speeds between 12 and 18 RPM (0.2 Hz and 0.3 Hz) must be avoided, because the pylon has an eigenfrequency of 0.29 Hz. Hence the range between 12 and 18 RPM would cause interference of the actual rotor frequency with the structures eigenfrequency that leads to severe structural damage. Another option to adjust the power output is to change the pitch of the rotor blades.

2. Measurement configuration

To enable a comprehensive analysis of the wind energy turbines deformations and oscillations, the whole structure was separated into 3 major regions of interest:

- The mechanical-electric power train inside the nacelle
- The yaw drive with the nacelle itself
- The entire pylon

The goal of this concept was to combine continuously sampling sensors with discretely measuring sensors. Table 1 gives an overview of the sensor position, the measurands and the overall time period of the acquired data.

Task	Sensor	Location	Observable	Time
1	Inclinometer	Stages inside Pylon	Inclination and oscillation of pylon	1 week
2	GPS	Top of nacelle	Nacelle azimuth	2 weeks
3	Laser scanner	Inside nacelle	Inclination of power train	6 min
4	Laser scanner	Ground	Inclination and oscillation of pylon	10 min
5	Tacheometer	Ground	Nacelle azimuth	1 day

Table 1: Used sensors, observables, sensor positions and time duration of measurement

The sampling rates of the sensors were chosen according to the nominal eigenfrequencies of the structure. The behaviour of a wind energy turbine as a dynamic system is affected by certain parameters. The following variables are important for the entire system:

- The wind load
- Periodic stimulation by the rotor frequency (1p), for example caused by rotor mass imbalances
- Periodic stimulation by different blade loads (3p), caused by lower surface pressure

Further frequencies can be derived through multiples of the 1p-frequency and the number of blades, for example 6p, 9p for 3 blades [1]. The first eigenfrequency of the pylon depends on its stiffness: Stiffer materials cause higher eigenfrequencies. The statics expression describing the stiffness of the pylon is “soft” or “hard”. Since the WET used for this paper has a first eigenfrequency of less than 0.5 Hz, it has a soft pylon.

3. Statics calculation of a Wind Energy Turbine (Finite Elements Model)

For a first static calculation of the WET the simplest condition was chosen. To have no load on the rotor blades, they were aligned in parallel position to the wind at low wind speed. In this case the WET can be considered as a cylinder with linear elastic behaviour [3]. Furthermore a uniform wind load was assumed for the calculation of the elastic line. Here, dynamic wind loads have not been considered. Since the tower of the WET has a conical form, it has no constant flexural stiffness. In addition to this the wind load cannot be accounted like a simple delta load. Using the finite element method, the tower was separated into 54 elements with different specific loads, each of which is bounded by two knots. After the calculation of the displacement vector, the single elements were recombined.

For the computation of a certain elastic line it is necessary to compute the impact pressure on each element. Therefore the wind speed at the height of each element needs to be computed based on the measured wind speed on the top of the nacelle at 85 m height assuming an exponential model. This model includes the roughness coefficient α of the surrounding earth surface:

$$\frac{v_x}{v_{85}} = \left(\frac{x}{x_{85}}\right)^{\alpha} \tag{1}$$

$v_{85} =$ Wind speed measured on the top of the nacelle at a height $x_{85} = 85\text{m}$ (2)

$$\alpha = \text{Roughness exponent} \tag{3}$$

With the wind speed at the height of each element, the impact pressure q_x can be written by:

$$q_x = 0{,}5 * \rho * v_x^2 \left[\frac{N}{m^2}\right] \tag{4}$$

The impact pressure for each element is introduced to the computation as a uniform load and computed for each static case by assigning a wind profile dependant delta load (Figure 2). In order to set up the differential equations the modulus of elasticity of steel and the geometric moment of inertia *I* of each element are needed. *I* is a geometric parameter depending on the shape and dimension of the object. For a circle with the radius *R* and thickness *dx* the parameter *I* can be obtained as:

$$\mathrm{I} = \frac{\pi}{4}\left((\mathrm{R} + \mathrm{dx})^4 - \mathrm{R}^4\right) \ [\mathrm{m}^4] \tag{5}$$

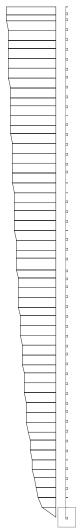

Figure 2: Impact pressure

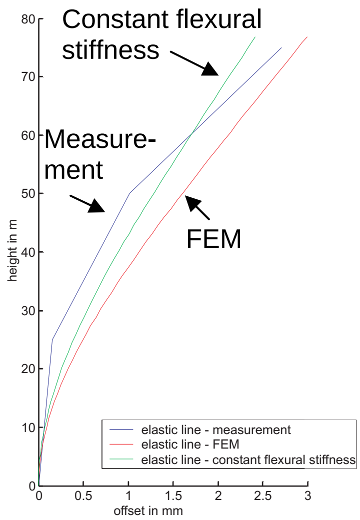

Figure 3: Elastic lines

The computation was done with the statics software Stab2D written by the Institute for Statics and Dynamics of the University of Hanover.

The computed elastic line is shown together with the elastic line derived through inclinometer measurements (Figure 3). An additional elastic line was computed with constant flexural stiffness along the height of the pylon. It can be seen, that the difference between both models and the measurements is large compared to the overall deformation of about 3 mm. This can be explained partially by the unknown parameters of the wind direction and only 3 discretely measured points. For a better approximation of model and measurements either a more complex model or a larger number of measurements at different height levels are needed.

4. Deformations of the pylon recorded with inclinometers

The bending of the pylon at various wind loads was measured with inclinometers. The sensors were mounted at heights of 25.9 m, 51.8 m and 76.9 m corresponding to the ends of the three pylon segments. Due to the high frequency of the oscillations induced by wind, only servoinclinometers are appropriate for data acquisition. The sensors on the first and the third level were of the type Rotlevel. These are dual-axis self-calibrating inclinometers primarily dedicated for the monitoring of slow deformations. Therefore the maximal sampling rate for measurements in two faces is about 60 s. If the tilts are measured only along one axis and just in one position like in this case a reliable sampling rate of 1 Hz can be obtained. The sensor on the second level was of type Schaevitz-LSOC. This is a one-axis inclinometer with an analogue output signal. The sampling rate was limited by the used analogue-to-digital converter at 6.1 Hz that was the fastest sampling rate upon all other sensors used in this campaign. In a test that consisted of measuring the tilts of a platform with adjustable oscillating frequencies all inclinometers proved to be adequate for this monitoring task.

The orientation of the inclinometers' sensitive axis was roughly the same for all inclinometers in order to assure the comparability of the data recorded at the different levels. However, the data dependency on the wind direction could not be avoided because of the fixed position of the sensors inside the pylon and the measuring in just one direction. Thus changes in the rotation velocities, in the orientation of the nacelle or in the pitch express themselves as changes of variability in the time series. These aspects need to be considered in the processing step by separately analysing data that refers to different states of the WET. The control software of the WET stores every 10 minutes condition parameters i.e. the power output, the rotation velocity, the azimuth of the nacelle. Hence the identification of stationary operating states of the WET is faciliated by this means. Additional to the changes of variability also variations of the mean of the data recorded with the Rotlevel inclinometers were encountered. They occurred due to the oscillations of the pylon during the self-calibration process, but could be detected visually and removed by subtracting the height of the jump from the subsequent data.

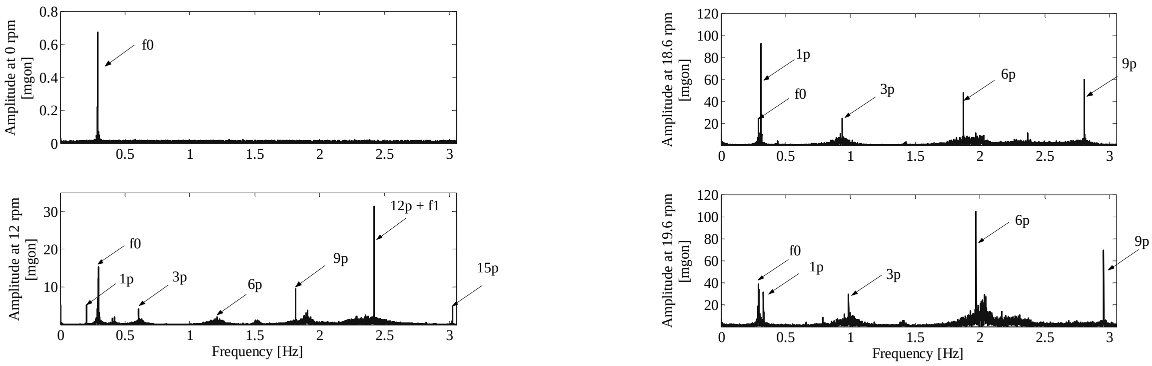

Figure 4: Amplitudes of the deformations of the pylon at various rotation velocities

The magnitude of the deformations was determined for rotation velocities of 0, 12, 18.6 and 19.6 RPM. Figure 4 shows exemplary their values obtained from the data recorded with the Schaevitz-inclinometer.

The frequency f0 corresponding to the eigenfrequency of the pylon is detected in all of the four states of the WET. Except of the larger value at 19.6 RPM the variation of its amplitude with rotation velocity is nearly linear. The peaks denoted by p are induced by rotation: 1p corresponds to the rotation frequency and 3p to the blade frequency. The other p-frequencies are higher order harmonics of the blade frequency. The amplitude of the 3p and 9p frequency varies linear with the rotation velocity. This linear variation cannot be accepted for the 1p and 6p frequencies because of the high unexpected values at 18.6 and 19.6 RPM respectively. The occurrence of these large values is not obviously related to rotation states of the WET. A possible explanation for them is the overlap with higher order harmonics of other effects as in the case of 12 RPM. It can be noticed, that the overlap of 12p with the second eigenfrequency of the pylon, denoted by f1, produces the highest peak in this spectrum although for other rotation states the 2nd eigenfrequency could not be even identified. However the explanation can be given only after consulting construction specialists.

In addition to the study of the pylon’s oscillations at different rotation velocities their variation with height was also analysed. The obtained results are presented exemplarily for the rotation state of 12 RPM. The spectra of the data recorded with the Rotlevel on the first and third level are shown in the left and right part of the following figure:

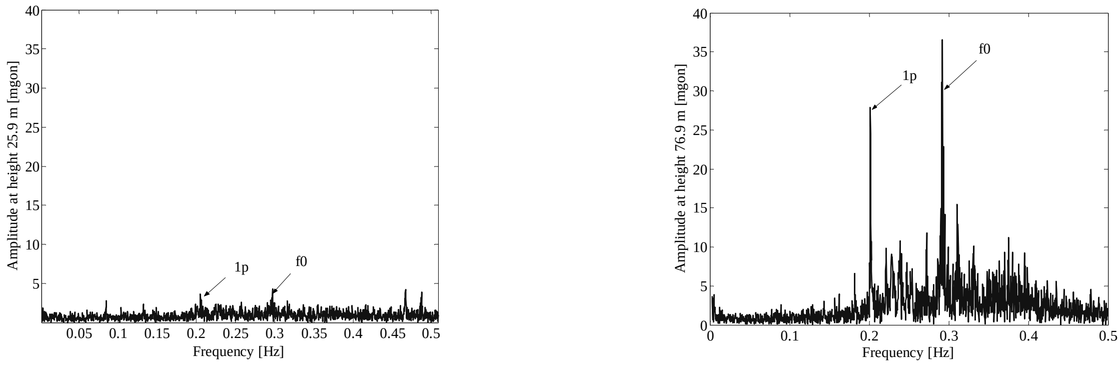

Figure 5: Amplitudes of deformations of the pylon at 25.9 m (left) and 76.9 m (right)

This shows that the first eigenfrequency and the rotation frequency 1p are also detectable with the Rotlevel sensors. The other dominant frequencies appear as aliases because of the low sampling rate. It is however impossible to detect them without their prior knowledge from a more detailed spectra as the one obtained in Figure 4. Compared to the spectra obtained from the Schaevitz data the ones in Figure 5 have a higher noise level and the ratio of the amplitude at 1p and at f0 is slightly different. This may be caused by the properties of the used sensors. The variation of the amplitudes at f0 and 1p over the height is not linear thus indicating a bending of the pylon under wind load.

In conclusion it can be stated, that inclinometers are appropriate sensors for measuring the pylon’s deformation. A good spectral information can be obtained for sampling rates above 5 Hz. If the sensors are measuring just along one axis their orientation relative to each other and to the nacelle should be determined accurate. The orientation task is less restrictive if one uses dual-axis inclinometers. The data which describes the state of theWET should be recorded with higher frequency because wind can change its intensity and direction several times in 10 minutes. However the dominant frequencies could be reliably detected with both types of sensors. Their amplitudes clearly show the dependency of the deformations on rotation states and height.

5. Measurements with terrestrial laser scanning

In addition a terrestrial laser scanner was used to detect deformations and oscillation frequencies of the whole pylon.

The scanner used for this task was a Leica HDS 4500 laser scanner, also known as Z+F Imager 5003. This scanner uses the phase measurement technique to determine the slope distance to the objects surface. It has a unique measurement range of 53.5 m. This means that beyond this range ambiguities have to be considered. The maximum data acquisition rate is limited to 625,000 Hz for the range determination. In the so called profiler mode the movement about the vertical axis is disabled so that a 2D profile of 310° is obtained. The data rate depends on the point density and the range accuracy and varies from 12 Hz to 33 Hz. This mode was used for the tasks 3 and 4 according to section 2.

Figure 6 shows the configuration for the presented profile measurements in plan view and Figure 7 in side view. The scanner position perpendicular to the wind direction was expected to deliver the most high deformations of the pylon. For further analysis of other viewpoints see [2]. The software used for this scans was Z+F Laser Control 6.6.0.0 with the scan parameters "SuperHigh" resolution (equivalent to minimum point spacing), "LowNoise" accuracy and "Far"-mode for range ambiguities.

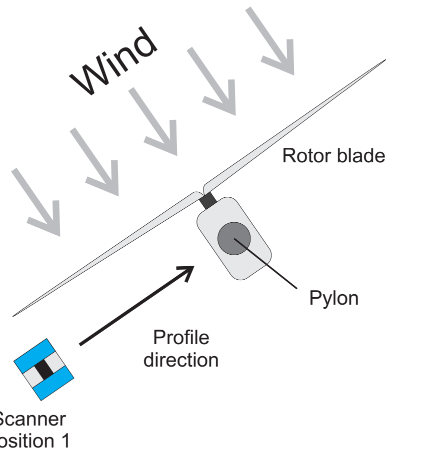

Figure 6: Measurement configuration for ground based terrestrial laser scanner (plan view)

The scan used for this analysis has an overall number of 60.2 million points. Along the vertical surface of the pylon several classes of equal width (2 m, 1 m, 0.5 m and 0.2 m) were defined (Figure 7 detail). The vertical mean of each class was defined by its position and vertical expansion, the horizontal value was variable because of the objects movement and had to determined through the median value of the scan points belonging to the certain class. So each class median represented one epoch for its corresponding class.

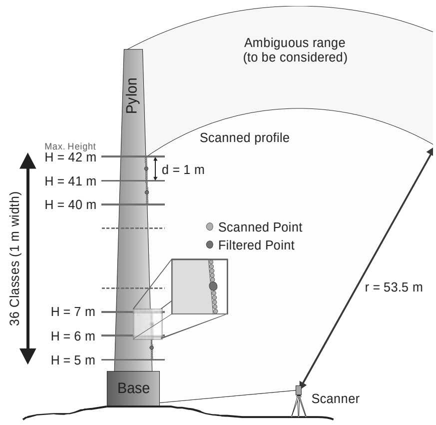

Figure 7: Measurement configuration for ground based terrestrial laser scanner (side view)

The resulting time series was optionally smoothed by a moving average filter (Figure 8). The time series was partitioned into a first and second part. Between the first and second part the WET changed its rotor pitch to enable a better power output. The orientation of the nacelle and the rotation frequency were unchanged. Figure 9 shows the amplitude spectrum of Part 1 with the pylon's eigenfrequency (0.29 Hz) and the rotor frequency of 0.31 Hz can be seen clearly. In Part 2 the rotor frequency has a higher amplitude than the eigenfrequency due to the mentioned change of the rotor pitch. This fact as well as other time series in combination with a principle component analysis can be obtained from [2].

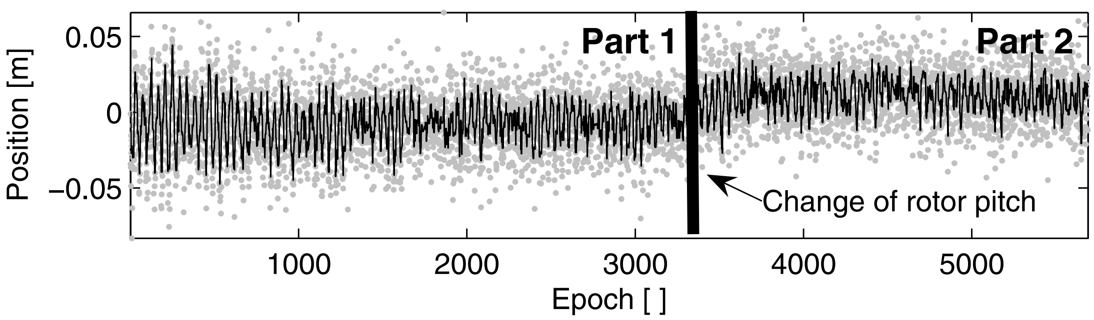

Figure 8: Time series of class-value at 51.8 m height (median filtered)

The amplitude spectra from height level 6 m to 51 m with an offset of 5 m each are shown in

Figure 9. It is obvious that the amplitudes of the pylon oscillations increase at upper levels. The empty class at 41 m height is a result of the minimum measurement range of the imager, because at this height, the slope distance exceeds 53.5 m. Although the ambiguity range can be extended by the processing software, there are no measurements between 53.5 and 54.0 m. In contrary to the inclination sensor data, no other frequencies except 0.29 Hz and 0.31 Hz are detected by this analysis (Figure 10).

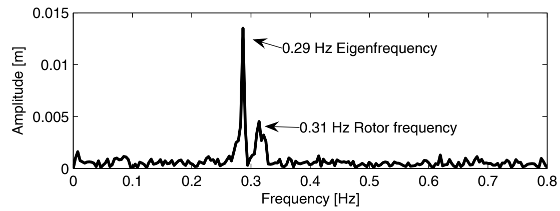

Figure 9: Amplitude spectrum of part 1

The second measurement took place at a WET in Göhl, near Lübeck (Germany). The task (task 4 according to section 2) of this project was to acquire the inclination changes of a fast moving axle between the gearbox and the generator which is part of the power train. This was done in WET, located east of Lübeck (northern Germany). In operating mode the axle rotates with a speed of up to 1500 RPM. The axle and the generator are coupled with a cardan joint so that tippings are applicable (Figure 11).

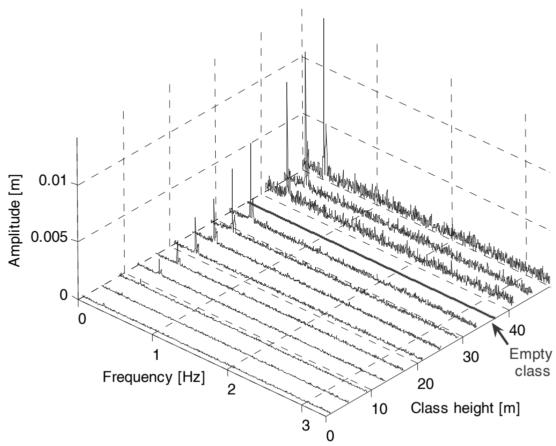

Figure 10: Amplitude spectra of classes of 6, 11, 16, 21, 26, 31, 36, 41, 46, 51 m height

The time series consists of 10061 profiles (615 sec). During the measurements four time tags were determined manually. After 139 sec the WET shifts to 800 RPM mode (Tag 1) and at 305 sec to highest rotation speed of 1500 RPM (Tag 2). An emergency braking procedure was initialized at 531 sec by turning the wing tips in square position (Tag 3). At 542 sec the wheel disc break was used (Tag 4) to enable a full stop. Since the generator had no unique surface, a flat plane was attached to the top of the generator housing that represents the inclination of the generator. The position and the inclination of the axle as well as of the plane was determined by linear regression. The angle between the axle and the plane varies with an amplitude of 0.25 gon (Figure 12).

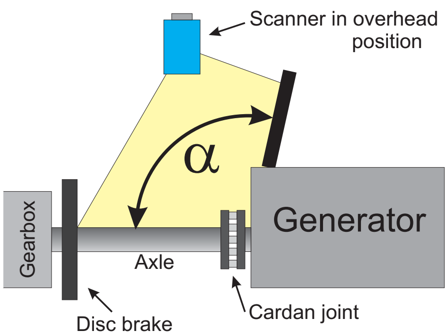

Figure 11: Measurement configuration

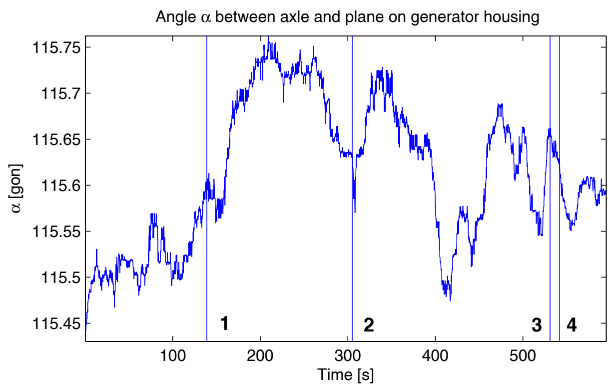

Figure 12: Time series of angle α

6. Measurements with GPS

Due to its high degree of automation and accuracy GPS is a suitable choice for a sensor to perform the monitoring of a WET. For about three days GPS data were recorded using the modern GPS receiver Leica GX1230, a 12-channel geodetic dual frequency receiver with the standard antenna AX1202. This system is designed with the SmartTrack-Technology which acquires all visible satellites within seconds and tracks these even at low elevations. The highly effective multipath mitigation and advanced antijamming are advantageous properties of this system especially useful in GPS-unfriendly environments like on the nacelle of a WET. The reference station was set up on top of the roof of a building nearby. The rover antenna was placed on top of the nacelle of the WET as shown in Figure 13.

The test measurements were performed from 01-12-2004 until 03-12-2004. The measurement rate was 1 Hz. The tracking conditions at the rover- and the base-site were quite different. Therefore one encounters a great difference in the number of simultaneously tracked satellites for computing the positions of the rover in kinematic mode.

Figure 13: Rover Station on top of the WET

The quality values of the recorded carrier phase and code data were calculated with the analysis program teqc (Translate/Edit/ Quality Check), that is available at Unavco (www.unavco.org). The S/N-levels at the rover station were marginally lower than at the base station. For this reason the data quality was considered as equal. The analysis of the root mean square values of the multipath signals MP1 and MP2 revealed that the data of the rover station is heavily influenced by multipath effects. In order to estimate the quality of the data the parameters of the data set are summarized in Table 2:

	Rover	**Base**
Default epochs (measured epochs)	174588 (172061)	159211 (159211)
Default observations (measured obs.)	1472373 (858011)	1364605 (1293753)
Deleted observations	2545	246
MP1 Slips	3614	58
MP2 Slips	3616	72
Signal Slips	36765	73
MP1 [m]	1.13	0.14
MP2 [m]	1.54	0.18

Table 2: Quality values as a product of teqc

The post-processing of the data was done using the Trimble Total Control Software. The determination and analysis of the kinematic point solutions turns out to be a difficult task. One the one hand the rotation of the blades causes a lot of signal interruptions and strong multipath effects as can be seen from Table 2. On the other hand changes in the orientation of the nacelle cause sudden deviations of the resulting coordinates as shown in Fig. 15. To reduce this effect a circle adjustment was done. The resulted radial residuals are depicted in Figure 14. Neglecting the nacelle's movement it is necessary to detect time intervals which correspond to a constant azimuth and to low standard deviations of the point positioning, e.g. less than 2 cm for each coordinate component. Thus five intervals without movement of the nacelle and additional six intervals with one or two movements were identified.

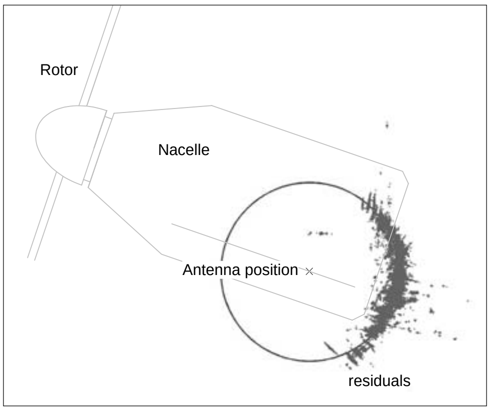

Figure 14: Radial residuals

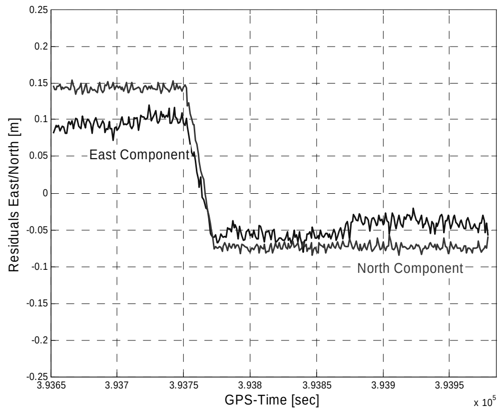

Figure 15: Time interval with good standard deviation and with nacelle movement

The dominant frequencies of these time series of East- and North coordinates were calculated using the Fast Fourier Transformation. The obtained amplitude spectra are shown in the Figures 16 and 17.

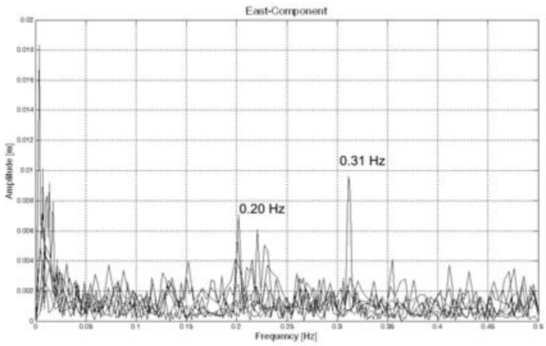

Figure 16: Amplitude spectrum of East-Component

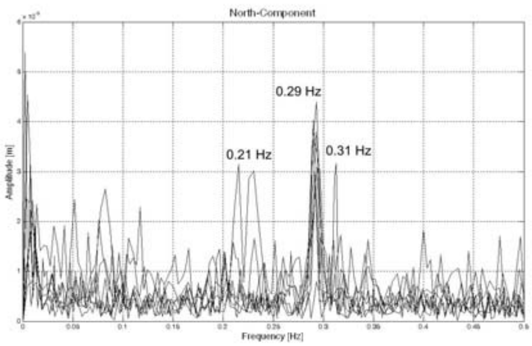

Figure 17: Power Spectrum of North-Component

The result of this analysis is that both components are influenced by the typical rotor blade frequencies. Additionally the eigenfrequency of the wind turbine occurs in the north component. Table 3 shows the standard deviations of the different point positioning methods.

	s_{East} [m]	s_{North} [m]	s_{Height} [m]
Kinematic solution rover	0.198	0.594	0.084
Kinematic solution rover (time intervals)	0.015	0.006	0.013

Table 3: Standard deviations of point positions

7. Conclusions

This paper shows that it is possible to use a broad range of geodetic sensors to implement a monitoring system for wind energy turbines. Although the results of the different sensors could not be compared in any case, it can be stated that the behaviour of all major parts of the structure can be described by the data. This includes the pylon, the nacelle movements as well as the inclination changes of the power train. The used sensors offer a sufficiently high accuracy for the determination of the objects deformations and their frequencies.

On the one hand continuous measurements with high sampling rates like inclinometer measurements are able to detect the complete spectrum of movements and oscillations. On the other hand sensors like terrestrial laser scanners are very flexible as they can be mounted quickly and deliver comprehensive data about the state and the deformations of a wind energy turbine. It has to be mentioned that the use of this sensor type requires the solution of ambiguities when operated in kinematic profiler mode.

In order to combine all the sensors to a integrated monitoring system, a precise synchronisation of the sensor times including the sensors for acquisition of environmental parameters has to be accomplished.

8. References:

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[2] Hesse, C., Neuner, H., Kutterer, H.: Statistical Analysis of Kinematic Laser Scans. In: Grün, A./Kahmen, H. (Eds.): Optical 3D Measurement Techniques VII, Vol. I, pp. 103-112, Vienna, Austria, October 3-5, 2005

[3] Horst, S.: Geodetic contributions to the monitoring of wind energy turbines (in German). Diploma thesis at the Geodetic Institute of the University of Hanover, (unpublished), April, 2005.