Monitoring of Concrete Bases of Wind Turbines with Modern Inclinometers: Approaches and Experience

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Key words: Wind Turbines, Foundation, Inclinometer, Condition-Monitoring-System, Statistical Analysis

SUMMARY

For dynamically highly stressed wind energy plants effective quality control is of vital importance. Dangerous defects in the concrete bases of wind turbines are known to be caused not only by external factors, such as temperature changes or fatigue of construction materials over the time, but often particularly by constructional defects or design failure. The valid standards and guidelines suggest specific measurement methods, descriptions and evaluations of existing cracks in the concrete base. The goal of the current research project at the Beuth University of Applied Sciences Berlin is to develop a new concept for an early identification of security-relevant defects within the fastening between tower and concrete base, in the form of a Condition-Monitoring-System (CMS). To apply existing techniques of a rapid alert system, specific algorithms have to be developed. Based on continuous measurements with modern inclinometers, these will allow a reliable and stable identification of significant deviations from the structure's "normal behavior". The already performed test measurements on wind turbines confirm that this method has a great potential in the assessment of wind turbine foundations and can be used for early warning systems.

ZUSAMMENFASSUNG

Für die dynamisch stark beanspruchten WEA-Bauwerke ist eine effektive Qualitätskontrolle von entscheidender Bedeutung. Es ist bekannt, dass gefährliche Defekte im Bereich der Betonfundamente nicht nur durch äußere Einwirkungen, wie z.B. Temperaturänderungen oder durch zeitabhängiges Materialverhalten, sondern auch durch verdeckte Baumängel und Planungsfehler hervorgerufen werden. Obwohl sich eine vorbeugende Überwachung der meisten Bestandteile moderner Windkraftanlagen im Rahmen von sog. Condition-Monitoring-Systeme (CMS) längst zu einem Standard entwickelt hat, befindet sich diese Vorgehensweise in Bezug auf die Fundamente und Fundamenteinbautele erst in einer Entwicklungsphase. Im Beitrag werden sowohl die grundlegenden Prinzipien für Kontrollen dieser Art als auch die konkreten messtechnischen Lösungen und Algorithmen der folgenden Datenauswertung exemplarisch behandelt. Bei der Messtechnik steht dabei exemplarisch der Einsatz von modernen Neigungssensoren im Mittelpunkt des Interesses. An Hand eines typischen Beispiels werden im Beitrag die Möglichkeiten dieser Lösung gezeigt und die unterschiedlichen Wege bei der Interpretation von Messergebnissen diskutiert.

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1. INTRODUCTION

Due to high investments within recent years, wind energy contributes significant parts of Germany's energy supply. Almost half of the existing wind turbines (Fig. 1) were built before 2006 and are within short time reaching their scheduled service life of 20 years. Besides the exploration of new suitable constructions sites, the maintenance of existing wind turbines is playing a major role. Actual and objective documentation and evaluation of existing damages and defects is crucial for this purpose. The last years showed that more and more problems arise around the link between steel tower and concrete foundation in turbines of several manufacturers. Circular or semicircular cracks in the concrete foundation outside and inside of the tower, as well as spalling on top of the foundation and resulting water ingress occur as typical damages (Fig. 2). A reason for those damages is an irregular movement of the tower within the foundation. Reasons for this could be construction defects or design errors. The earlier these kinds of defects are detected, the higher are the chances to prevent a shutdown or very costly restorations of the damaged turbine.

Figure 1. Typical wind turbines

In the last decades huge progress within the field of microelectronics, computer science and communication technology has been made. This provides new technical possibilities to survey and

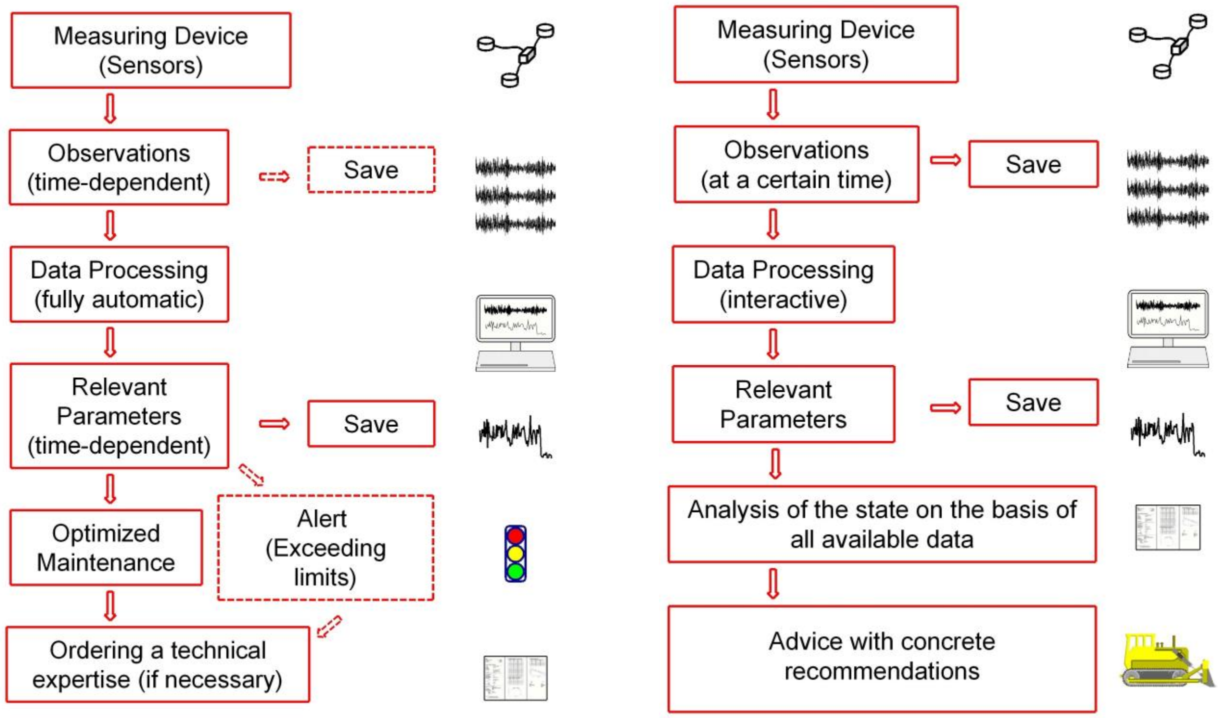
Spalling inside | Spalling outside | Water inlet | Circumferential cracks

Figure 2. Typical defects of foundation in wind turbines

monitor the actual condition of endangered structures. In most components of a wind turbine, such as the rotor, the transmission, the generator as well as the nacelle positioning etc., automatic preventive monitoring is already industrial standard and referred to as "condition monitoring systems" (CMS). Thus, irregularities within spindles, bearings and cogs can be detected early and without unmounting the complete drive train. Despite the known problems and diverse technical possibilities (GRÜNBERG & GÖHLMANN 2013), CMS have not been established to monitor the foundations of wind turbines to this day.

2. CHARACTERISTICS OF MONITORING

Just like in other applied condition monitoring systems, the condition monitoring of foundations has to be effective as well as reasonably priced. Unlike specific measurements and expertise, a CMS control serves the purpose to prevent dangerous events, such as the crash of the whole construction, and moreover to optimize maintenance and repair. The former occasion is quite improbable and can be excluded by singular measurements and regular expertise. The latter (optimization) is to detect potentially damaged wind turbines by the information gathered through CMS, and then initiate continuative measurements and expertise that lead to a restoration of the structure. Like this, a priority list can be developed, that distributes the expenditures wisely.
As a result of a common structure monitoring, various characteristic data (e.g. acceleration,



Condition-Monitoring-System Expertise

Figure 3. Expiry of metrological state control

inclination, displacements etc.) are measured in order to quantify the condition of the observed structure. Based on these measurements, the condition must be described by certain parameters and an alerting system, categorizing the condition ("good" or "safety relevant"), has to be developed. An accurate visual analysis of all gathered monitoring data, with up to hundreds of sensors within a construction, is nearly impossible, due to the extensive amount of data collected over a long time span. In general, in monitoring, the aim is to extract certain characteristic parameters and features from raw data. From these parameters significant deviations of damaged structures from the parameters of structures in good condition, describing the “normal” behavior, can be detected. This pre-processing of raw data must be automated in condition monitoring systems, unlike in singular measurements. In addition, an evaluation in the form of an alert system (stop light) must be included already at this stage.

Still raw data has to be stored to be accessible for a specific analysis after a warning has been sent and an expertise is initiated. Many methods for technical expertise of wind turbine foundations have been developed by now, which however are mostly based on visual analysis of cracks and one time manual measurements and thus are subjective. The gathered data of a condition monitoring system deliver something like a “medical history” of the building and allows an objective analysis and evaluation of changes in the structure’s behavior over long time spans. Hence, the storage of all raw data (Fig. 3) can be potentially useful, even though it is not an inevitable part of a CMS yet.

3. CONCEPT OF MEASURING SYSTEM

According to official guidelines, a regular control of the tower’s misalignment is recommended. Except from threshold values (3 mm/m without ambient influence, 5 mm/m considering one-sided solar irradiation), no information is given concerning technical procedures or interpretation of the latter. Irregular settling of the foundation soil or the foundation itself, have to be controlled directly at the foundation or the first connection flange of the tower. These results are free from ambient effects, such as one-sided thermal extension, and thus significant. In the new guidelines a control of the misalignment at the base and at first flange is demanded. The basic idea is not to detect damages within the tower itself, but within possible weak points, that is to say the link between tower and foundation.

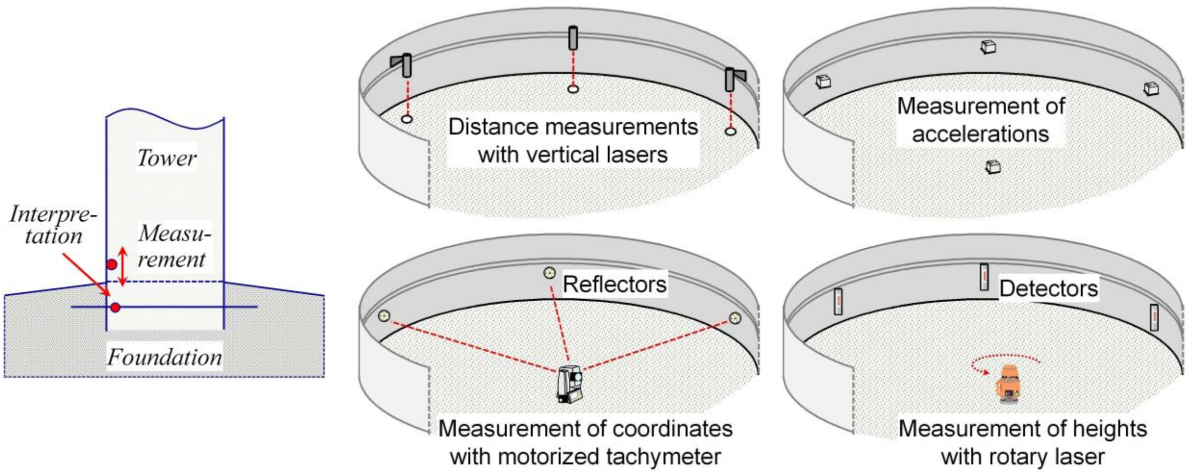


Figure 4. Typical measuring systems for monitoring

Even though the aim of the here developed measurement and evaluation methods is defined as a control of physical processes within the concrete foundation, measurements on its surface and at the side of the tower wall can show certain advantages for the interpretation of deformations. There are several measurement technologies that can be used to monitor the condition of the foundation.

Different solutions have been tested in recent years, based on accelerometers, motorized tachymeters and specific laser systems (RESNIK et al. 2013 -2017). Some of such measurement methods are presented in the Figure 4.

The here described system is based on several inclination sensors, that are situated on the first flange and directly on the foundation inside the tower and are connected to a measurement computer. In the course of the research project (WESAFE 2016) the measurements were realized by using Leica^R Nivel precision inclination sensors that was shown to be a highly precise and reliable instrument for our purposes. It is a two-dimension inclination sensor, working by a fluid-based opto-electrical measurement principle. The advantages of the sensor are its very high resolution and measurement accuracy, independent of electrical fields, and an extensive calibration guaranteed by the producer. Due to the liquid based construction, the sensor is inert, which does not allow sampling frequencies of above 6 Hz. In addition, it is limited to a quite small measurement range of less than 1°, which can lead to problems during installation and expected deformations. Also, the sensors are relatively costly, which allow their usage in an expertise, but not in a broadly installed long-term condition monitoring system in many wind turbines. If there are cheaper, commercial

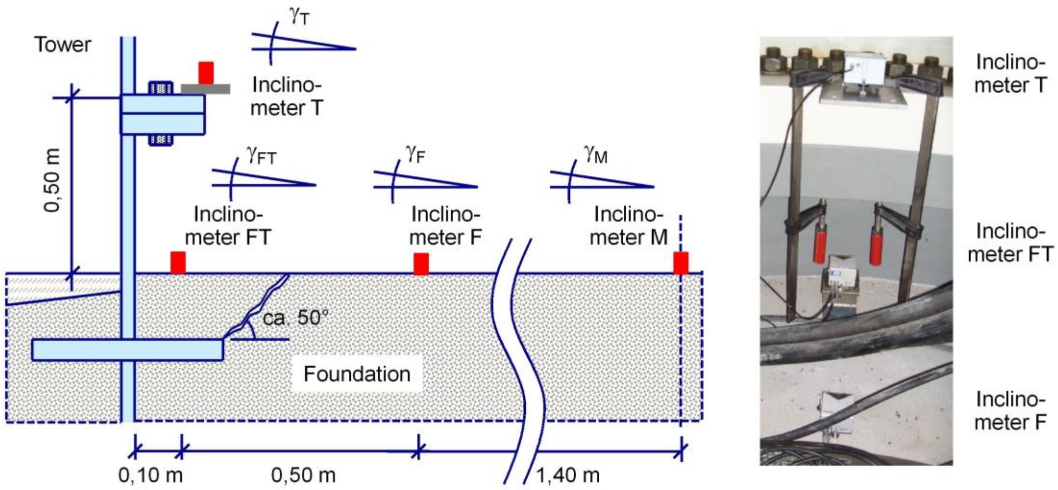


Figure 5. Measurement system based on inclination sensors (example)

sensors on the market, that can fulfil the required accuracies, is being investigated at the moment and cannot be answered for now.

The choice of measurement locations is of the same or even more importance than the choice of measurement equipment. A technical control system using inclinometers can be realized as described in Fig. 5. One can assume that the foundation built-in part was mounted with a decent accuracy during the construction of the wind turbine. Hence, a measured misalignment represents a subsequently occurred change on the base of the tower (***inclinometer T***). If in following measurements with different wind directions significantly different values of misalignments of flange to foundation are identified, there is a high probability that this was caused by defects in the bonding between tower and foundation. If the built in part moves together with the foundation base, as expected, it results in vertical and horizontal tension and therefore cracks in the concrete in a certain distance of the tower wall. This distance is determined by the depth of the installed pressure plate and the break angle, which usually lies around 40-60°. This means that for a usage of two sensors on two independently moving parts of the foundation, one has to be located near the tower wall (***inclinometer FT***) and one in the distance of at least double the depth of the installed pressure plate (***inclinometer F***). All sensors (T, FT and F) can be positioned multiple times in different angles from the tower centre, to detect differences depending on wind direction. However, the sensors FT and F on the foundation consider only cracks related to the upper pressure plate of the built in part. An additional sensor in the middle of the Tower (***inclinometer M***) allows monitoring additional tensions and defects in the foundation, while directly comparing results of the other installed sensors.

4. CONCEPT OF DATA ANALYSIS

It is known that the quality of a fault diagnosis in the course of a typical monitoring and its cost efficiency are highly dependent on the applied signal processing algorithms. As discussed in chapter 2 it is crucial for a CM-Concept to extract characteristic parameters from raw data. For the subsequent analysis the data has to be processed appropriately. The here described method starts by dividing the data in specific time segments. The characteristics are calculated for each time segment and is further analysed and treated as a new time series.

In the first step, the data must be prepared for further interpretation. The inclination sensors used in this project measure inclinations in two orthogonal directions. These axes are further called "radial" and "tangential", related to the centre point of the tower. Both sensors were installed parallel to guarantee a common coordinate system. The extensive measurements taken in the wind turbine parks showed that inclinations on different locations often indicate different orientation in this coordinate system. Therefore, the cartesian values, γ_X (radial) and γ_Y (tangential), must be transformed to a polar coordinate system (γ_A, t_A). Value γ_A describes the maximum value of the misaligned base plane and value t_A describes the angle of the misaligned plane. For other purposes other coordinate systems can be defined, e.g. a primary wind direction oriented system.

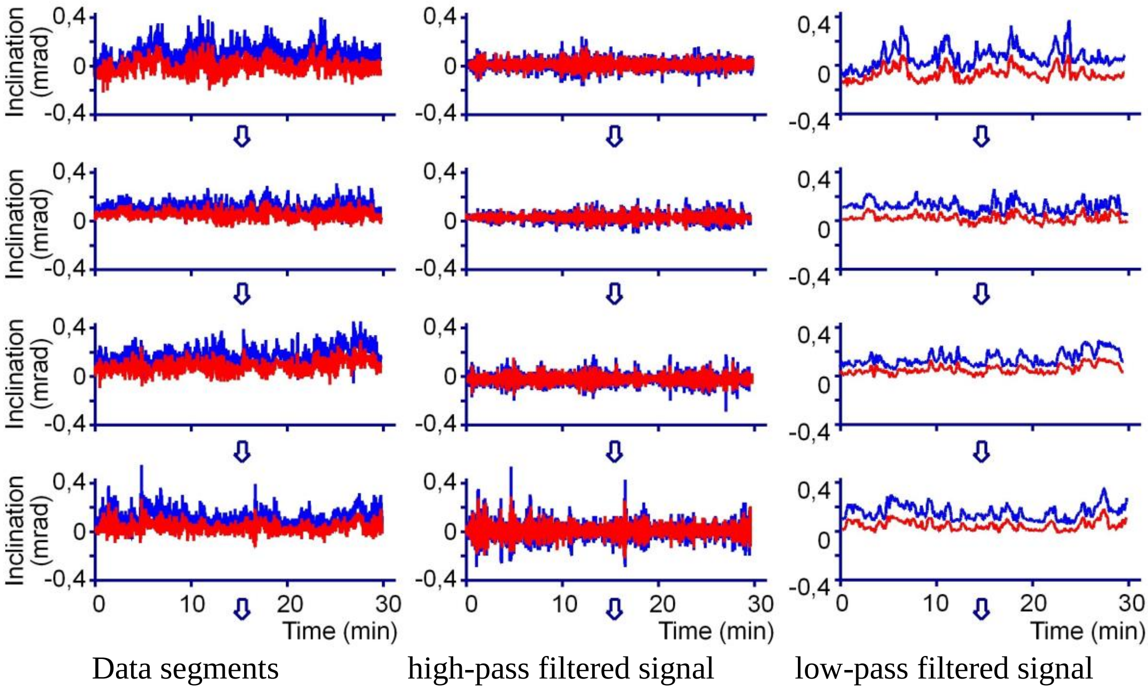


Figure 6. Filtering of the measured data (example, sensor FT – blue and sensor F – red)

Furthermore, the original measurements revealed that the gathered changes in inclination are composed of two different characteristics with different physical and therefore mathematical origin:

– fast changes in inclinations with frequencies between 0.1 Hz and 1.5 Hz (sampling rates of 3Hz),

– slow changes in inclination with cycles of <<10s, caused by "systematic" influences.

Therefore, the according time segments are processed by a frequency filter with a separation frequency of ~0.2 Hz. Like this there is two time series for each time segment, one containing only the high frequencies up to 1,5Hz of the signal, the other containing the low frequencies. The high-pass-filtered signal can be compared with the measurements of the acceleration sensors. The low-pass-filtered signal displays the relatively slow, "systematic" changes within the measurement. These are e.g. based on meteorological or technological parameters like one-sided wind pressure or nacelle position. The results of the analysis of a typical example are shown in Figure 6, in which four time segments of 30 min of the sensor near the tower wall (inclinometers FT and F in the figure 5) are displayed.

In the here described and widely tested CM-Concept of signal acquisition and processing the average characteristics of the measured time series are analysed, unlike singular events such as wind gusts. To obtain information about the condition of a monitored object (here: concrete foundations of wind turbines) out of a limited dataset (here: change in inclination at different locations), statistical analysis tools are required. To rate the observed correlations, the acquired stochastic parameters (here: standard deviation σ) are used as a test value. Their absolute values on each location are dependent on the different meteorological parameters wind speed and direction, nacelle position, which are not accurately known. Therefore, the ratio of standard deviations σ_1/σ_2 is used as the major control parameter. This method only makes sense from a certain wind speed and therefore sufficient values in the measurement. A threshold value of three times the noise is used. In this case the standard deviation ratio is calculated and saved.

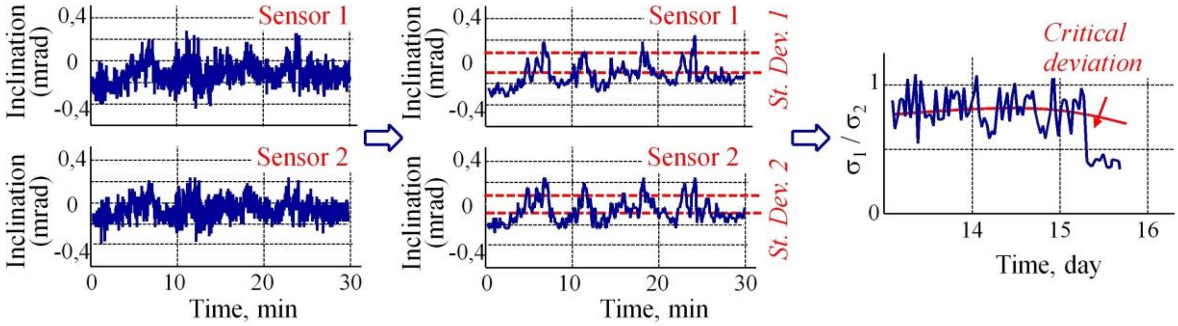


Figure 7. Concept of signal processing

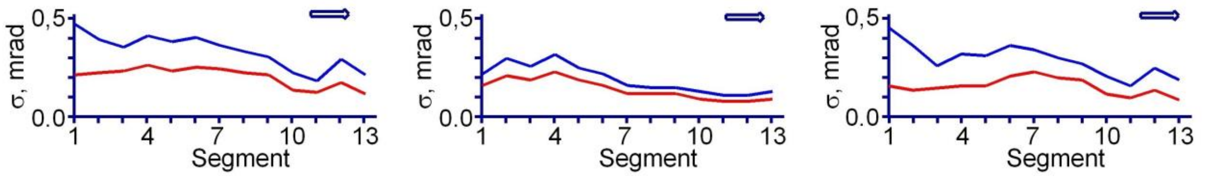
The whole concept of signal processing based on the above mentioned steps is displayed in figure 7. The biggest advantage of this proceeding is that the obtained information can be gathered systematically for years and analysed together with other wind turbines of the same type. Such an examination up to the presentation of specific suspicious damages can be automated and therefore complies with the requirements of a condition monitoring (Chapter 2).

5. RESULTS OF SELECTED TEST MEASUREMENTS

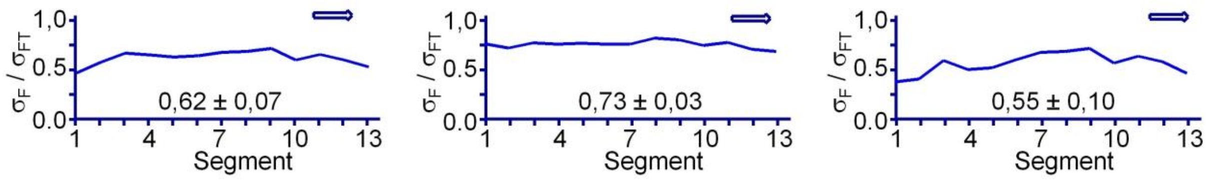
To prove the suitability of the described methods for an early stage recognition of damages in wind turbine foundations, it has to be tested on turbines of same type and different condition simultaneously, ideally over several years. In both cases, the condition has to be verified by using different non-destructive methods and surveys. In this article the proposed method is presented by a practical example, in order to find and justify an optimum constellation of sensors for a long term condition monitoring of this kind. The investigated object is a typical 2MW wind turbine with a steel tower and concrete foundation that was monitored with multiple sensors over several weeks. Because the description of all tested methods would go beyond the purpose of this article, only the data of the described sensors F and FT (Fig. 5) are presented in detail. Thirteen subsequent time segments of 30 min were selected, in which ideal conditions of wind speeds between 6 and 10 m/s in 100m height were observed.

Figure 8 shows the results of sensors F and FT on both sides of the visible circular crack in the observed turbine. The original values σ_A are presented, as well as the high-pass filtered and low-pass filtered data. The substantial changes in amplitude of both sensors can be explained by varying wind speed and direction. The noted correlation coefficients between both sensors, however, show values around 0.6 and confirm the hypothesis that the ratio between those amplitudes is stable over time and outer circumstances. The low-pass filtered data show a growth in correlation coefficients to around 0.9 and practically show a functional behavior. The high-pass filtered data shows a lower value of around 0.5. This time series represents a certain amount of noise of both sensors that are not at all correlated. As seen in the time series of ratios of standard deviation σ_F/σ_{FT} after applying the high-pass filter, they show a constant correlation value of 0.7. This value was confirmed by other parallel measurements with acceleration sensors at the same measurement locations,

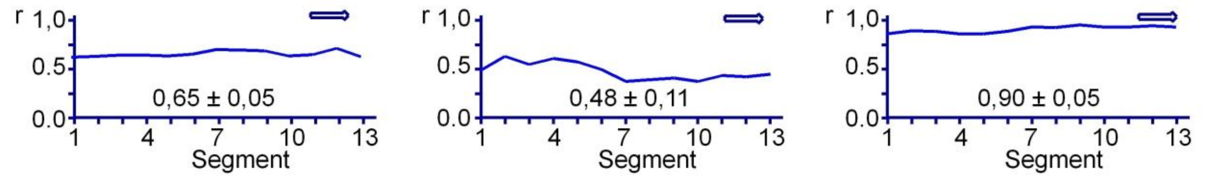
Original values: High-pass filtered data: Low-pass filtered data:



Standard deviations of the measured inclinations (FT – blue and F – red)



Ratio of standard deviations of both sensors

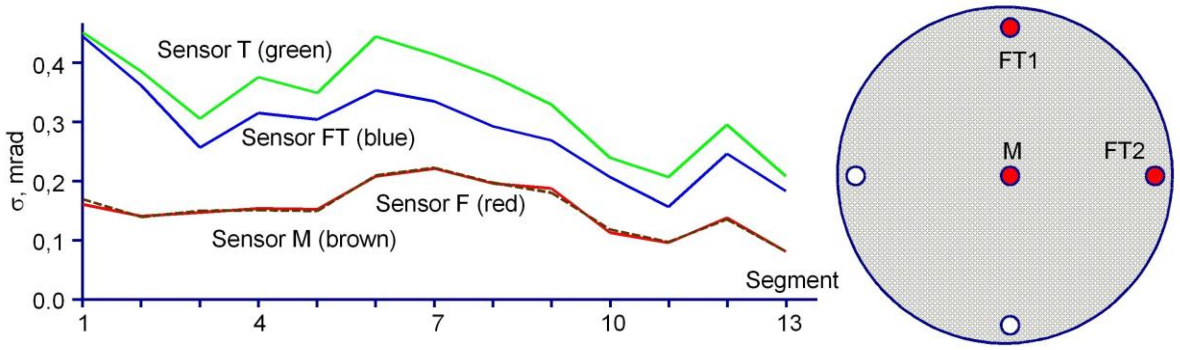


Correlation coefficient between inclinations of both sensors

Figure 8. Results of test measurements with sensors F and FT (example)

reassuring the quality of the applied analysis. The deviation ratio of the low-pass filtered data, however, is significantly lower and instable.
Assuming that a modern wind farm consists of up to 30 wind turbines, it is obvious that the number of sensors and their maintenance, supply and installation costs have to be minimized. The analysis of the results gives the opportunity to define promising sensor distributions for the required purposes, while keeping their costs low.

Based on the results one can assume that the built-in part moves together with the surrounding concrete parts of the fundament (Fig. 9, left). Even though the data between Sensor F and Sensor T, just as between Sensor F and Sensor FT, showed significant differences, its interpretation showed to be more difficult than for the latter. The differences can be caused by tension along the circular cracks or by the tower misalignment showing at the installation height of the sensor. Both processes occur at the same time and are therefore hard to separate during post processing. For those reasons the usage of Sensor T is considered unnecessary for our purposes. Between Sensors M, in the middle of the foundation, and F outside of the crack there is no significant differences, especially in the low pass filtered signals. Hence, multiple sensors outside the circular crack can be replaced by one sensor in the middle (M).



Results of test measurements (low-pass filtered signal) Sensor setting

Figure 9. Final assessment of results

The optimum solution for a measurement arrangement based on these results is therefore given by three or five sensors on the foundation (Fig 9, right) that can be advised for a following test phase of the algorithm.

6. CONCLUSION

The interpretation of the gathered monitoring parameters (a ratio between standard deviations of time series at different sensor locations) is similar for both measurements with acceleration sensors and inclination sensors. The signal's energy and therefore amplitude decreases during its propagation with increasing defects and wider cracks. With higher loss in signal energy, the standard deviation ratio decreases. Hence, the ratio is directly connected to the defective signal transmission behavior of the structure and can be used to evaluate its condition.

The broad measurements in different wind turbines in recent years showed a great potential of the presented method to identify defects in wind turbine foundations with the help of inclination sensors. In contrast to the use of acceleration sensors the requirements to accuracy (~1 mrad) and calibration issues (nonlinearities, temperature dependency) have to be realized with low-cost sensors. For an analysis of high-frequency dynamic processes therefore acceleration sensors are advised. An analysis of low-frequency deformations with cycles of >10 s (here the low-pass filtered inclination data) cannot be replaced by a system based on acceleration sensors and therefore is of high information value for this purpose.

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