Wireless monitoring of structural components of wind turbines including tower and foundations

B Wondra, M Botz and C U Grosse

Chair of Non-destructive Testing, Technical University of Munich, Baumbachstr. 7, 81245 Munich, Germany

bernhard.wondra@tum.de, max.botz@tum.de, grosse@tum.de

Abstract. Only few large wind turbines contain an extensive structural health monitoring (SHM) system. Such SHM systems could provide deeper insight into the real load history of a wind turbine along its standard lifetime of 20 years and support a justified extension of operation beyond the original intended period. This paper presents a new concept of a wireless SHM system based on acceleration measurement sensor nodes to permanently record acceleration of the tower structure at different heights. Exploitation of acceleration data and its referring position on the turbine tower enables calculation of vibration frequencies, their amplitudes and subsequently eigenmodes. Tower heights of 100 m and more are within the transmission range of wireless nodes, enabling a complete surveillance of the tower in three dimensions without the need for long cabling or electric signal amplification. Mounting of the sensor nodes on the tower is not limited to a few positions by the presence of an electric cable anymore. Still a comparison between data recorded by wireless sensors and data recorded by high-resolution wire-based sensors shows that the present resolution of the wireless sensors has to be improved to record accelerations more accurately and thus analyze vibration frequencies more precisely.

1. Introduction

Large wind turbines are designed for an operation period of 20 years. This design is based on statistics of wind conditions at the intended location of the turbine. However, permanent monitoring of wind and its effects onto the wind turbine enables deeper insight into the real load of all turbine's substructures. To extend the permit for its operation in Germany by local authorities, a wind turbine needs to be investigated with respect to both overall performance and particularly structural components, including the foundation and the tower. Structural safety, stability of the construction and residual service life have to be evaluated [1].

However, a onetime assessment (using for example non-destructive testing methods) of all structural components is time-consuming and not very efficient. Such assessment cannot provide comprehensive load history data. On the contrary, continuous monitoring of structural behavior can provide such comprehensive data, resulting in detailed insight into the turbine's structural performance. In turn, the understanding of the turbine's behavior allows prediction of its durability and residual service life. The complete load spectrum can be evaluated, including also dominant singular events which contribute significantly to the wind energy plant's deterioration. To date, most techniques related to structural health monitoring (SHM) for onshore wind turbines are

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developed to monitor the rotor blades or nacelle components [2], [3], [4]. By contrast, SHM techniques were applied to offshore wind turbines to also detect behavioral changes of tower structures [5]. In the presented approach, we concentrate on the structural components, but the overall data processing is open in a way that data from condition monitoring or rotor blade monitoring systems can be included.

2. The MistralWind project

The project MISTRALWind (Monitoring and Inspection of Structures At Large Wind Turbines) was initiated in 2015 and is supported by the German Federal Ministry for Economic Affairs and Energy. Within the next years, many wind turbines will reach their end of standard service life of 20 years. Still operation and maintenance of these wind turbines can be economically reasonable, if the structure's safety can be guaranteed. Thus, the project aims at development of a concept to extend safe operation of wind turbines beyond the standard of 20 years. The partners of the consortium come from the academic area, developers of testing and qualification systems, construction industry and manufacturers of wind turbines. The project includes investigations at real wind turbine structures as well as at test beds under controlled conditions. A more detailed description of the project can be found under https://www.zfp.tum.de/index.php?id=80

3. Wireless monitoring

Most existing SHM systems utilize traditional wire-based sensor technologies, typically using a large number of sensors (i.e., more than ten) which are connected through costly long cables and therefore will be installed on a few structures only. A wireless monitoring system with Micro-Electro-Mechanical-Systems-based (MEMS-based) sensors (microsensors) could reduce these costs significantly. Such systems have been extensively studied by many groups for different applications (s Lynch [6], Smarsly [7], or Feltrin [8]). The following developments are based on own former research projects [9], [10], [11], while we present a new concept of wireless acceleration sensor nodes located at the turbine's structure for analysis of wind-induced vibration. The contribution of acceleration measurements towards lifetime analysis is shown in figure 1. A comprehensive set of acceleration data over time is recorded and used for calculation of modal parameters (operational modal analysis, OMA), for instance natural frequencies, eigenmodes and damping of eigenmodes. Recorded acceleration data is utilized as an input to adapt and optimize a finite-element-method (FEM) model of the tower structure. Based on the FEM model, the time series of recorded acceleration data is converted into a time series of local displacements and strains. The FEM model is developed by project partners, as well as the analysis of material properties of the tower structure. Based on the material properties, strains are converted into material stresses. As a last step, stress cycles over time are accumulated and compared to data of stress-cycle curves. Residual service life of tower structure at average expected load can be estimated.

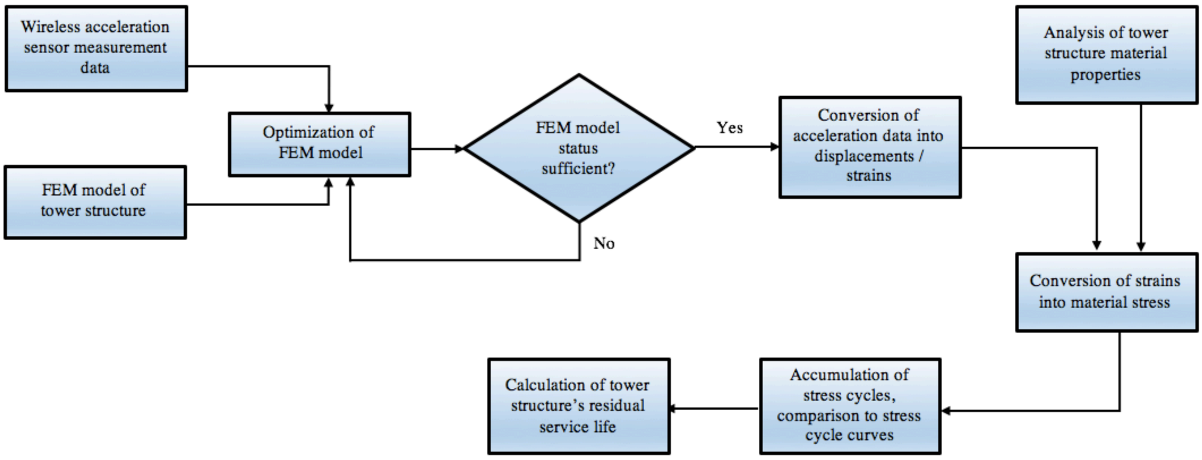

Figure 1. Flow chart of lifetime analysis from acceleration measurement data

Lifetime analysis of foundation or rotor blades are not part of this study, but require separate investigation. Vibration of rotor blades can obviously result in additional vibration of tower, but the FEM model does not include the structure of the blades. Subsequently, analysis of blade deterioration is not performed. The foundation is not modeled in detail, but interpreted as a firm base. Resolution of the accelerometers of wireless sensor nodes is not sufficient to record accelerations at the connection point between foundation and tower.

At this concept, the data processing takes place on the chip of the sensor node. The wireless approach features several advantages compared to conventional wire-based connections: Cost savings due to easy installation, flexible initial positioning and re-positioning of the sensor nodes, updating of measurement software over-the air and extension of the number of sensor nodes without additional installation of cables. The cost savings are based mainly on the elimination of wiring, its installation, maintenance and replacement. As modern multi-megawatt wind turbines reach tower heights of 140 m, wire-based solutions sometimes require signal amplifiers. As a contrast, a dense monitoring network based on wireless sensor nodes features flexibility at low costs, yet providing very detailed information of the structural state. Maintenance schedules for the structure can be optimized with regards to time and costs [12].

In case of absence of behavioral changes prolongation of service intervals can be recommended, appearance of significant changes in the structural behavior and its analysis by the surveillance staff will trigger a physical inspection, either by means of non-destructive testing or visual methods. Recorded behavioral change can be compared to recommended limits derived from a failure mode and effect analysis (FMEA) model. The comparison supports assessment of the detected change [13] and provide advises for suitable countermeasures. Such immediate repair reduces the risk of subsequent damage. Linked with proper system models, predictive maintenance scheduling is achieved and actual macroscopic failure is avoided. For continuous load history monitoring, recorded data needs to be transmitted recurringly to the supervisor, e.g. via internet or short message service (SMS) protocols. Each sensor node is a self-contained unit and requires its own energy supply, for instance by battery or energy-harvesting techniques [14]. Complete radio transmission of all acquired raw data would result in a low number of sensor nodes per gateway and a short battery lifetime of the nodes. Short battery replacement intervals, however, limit the usefulness of such wireless monitoring system for long-term continuous operation. Thus, raw data has to be processed by the microprocessor on the sensor board down to significant parameters before radio transmission. Longer periods of low wind velocity can be used to send the sensor nodes to a hibernate mode and to save battery lifetime. Once the wind speed exceeds the minimum threshold for power generation and the turbine operation is started, the wireless sensors can be activated by software command. If the tower movement at low wind speed contributes significantly to fatigue, as observed at offshore conditions (low resonance frequency and wave-induced vibration), the sensors can be set to record acceleration less frequently, e.g. once every ten minutes in order to reduce electric power consumption and to enhance battery lifetime. Data can either be transferred by the sensor node shortly after recording or alternatively collected for a determined period. The complete data package is announced by a start sequence, then transferred and finalized with a check-bit.

Various network topologies are known per today, including the star and the multi-hop topology [15]. The entire monitoring system has to withstand a rough environment and be resistant against oil, fuel, salt, alkali and other chemicals. The boards are developed for rough environment, mounted in sealed enclosures following the international protection IP64/65 standards of water protection. The sensors have to be robust and durable so that their measured data is reproducible and reliable over the monitoring lifetime. Furthermore, the system stability, which includes the wireless data transfer to and from the sensor nodes, must be high.

4. Combination of different physical data

Comparison of recorded data between independent measurement systems improves reliability and accuracy of the monitoring setup. This project exploits several techniques that are discussed in [16]: Wireless acceleration sensors for vibration recording, wire-based three-dimensional (3D) acceleration sensor as a parallel monitoring option for vibration, a seismometer for velocity detection, strain gauges for bending measurements and temperature sensors for adjustment of thermal expansion. Further methods of motion measurement are still under consideration, e.g. a fiber gyroscope for recording of rotational speed, camera-based video recording and laser vibrometry for distance measurements. In parallel, the supervisory control and data acquisition (SCADA) system of the wind turbine records further parameters such as wind speed and direction of wind every 5 minutes. Due to the timestamps of acceleration measurements and of SCADA data, potential correlations can be analysed. The sensor nodes themselves in their present setup are not programmed to receive data from external measurements, but a modified firmware in the future could enable receipt of external data and analysis on the sensor node chip.

Beyond the analysis concept shown in figure 1, the comprehensive amount of data enables further methods of data evaluation. The objective of this data mining is to find a characteristic feature of deterioration and a clear online representation of the real-time structural condition. The higher the number of independent measurements pointing towards the same event with a similar interpretation, the easier for the supervisor at a remote control center to take necessary countermeasures.

5. Wireless sensing developments

In collaboration with the University of California in Berkeley, USA, wireless sensor nodes have been developed to monitor structural parameters of infrastructure buildings such as bridges. These sensor nodes have been further developed separately at the University of Stuttgart (former research group of Prof. Grosse) and at Berkeley. The Berkeley development aims at the recording of environmental properties to control the Californian State water reservoirs [17]. This is the largest wireless sensor network in the world comprised of 720 stations and over 1200 sensors.

New, ultra-low power wireless sensing network hardware has been recently developed in Prof. Glaser's laboratory and at Metronome Systems LLC (metronomesystems.com). The so-called NeoMote, figure 2a, for example, consumes only 30 µA average in standard operation mode respectively 60 μA in an operation mode for driving external high-precision analog sensors, at a voltage of 3.6 Volts, resulting in an electric power consumption of 0.1 to 0.2 mW. However, wireless data transmission by an omni-directional BNC style antenna contributes significantly to the overall power consumption. Given a Lithium-ion battery mono D with 19000 mAh and 3.6 Volts to power one sensor node, the expected uninterrupted operation lifetime without battery exchange is limited to several months, depending on the amount of transmission time. The sensor node interrogates more than 40 analog and digital sensors simultaneously, and maintains a full mesh network with up to 500 meters of range.

The gateway "Network Manager", figure 2b, coordinates the sensor network. It interrogates the individual NeoMotes and transfers the received compressed data, either to local storage (SD card or USB stick) or to a remote server via cell communication or modem.

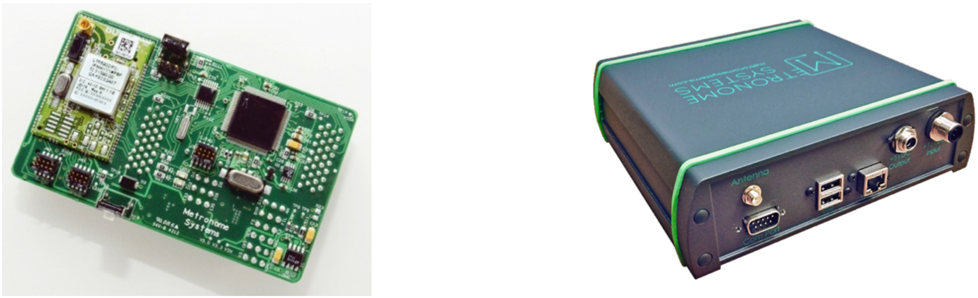

Figure 2. Metronome's NeoMote wireless sensor node (a) and gateway "Network Manager" (b)

6. Measurement campaign

A set of five sensor nodes were installed at an existing 3 MW onshore 3-bladed horizontal axis wind turbine in Bavaria, Germany. The design of this wind turbine is a concrete-steel hybrid tower with a hub height of 140 m and a rotor with a diameter of 113 m. Concrete section and steel section are connected at an altitude of 80 m. Three nodes were mounted on platform 1 of the plant, figure 3a, approximately 80 m above ground. Two further nodes were mounted on platform 2, figure 3a, at an altitude of 140 m, right below the nacelle, figure 3b. All nodes were positioned close to the center of their platforms to guarantee an unblocked transmission path to the gateway on ground level. Due to the present status of the software, each node recorded accelerations perpendicular to the node's circuit board. The largest movements of the tower were expected to happen perpendicular to the tower axis (z axis), either in direction of x axis or y axis (figure 3a). Thus, the sensor nodes were positioned to record accelerations in x and y direction. Signals both from sensor nodes on platform 1 and platform 2 were recorded by the gateway on the ground without usage of signal amplifier.

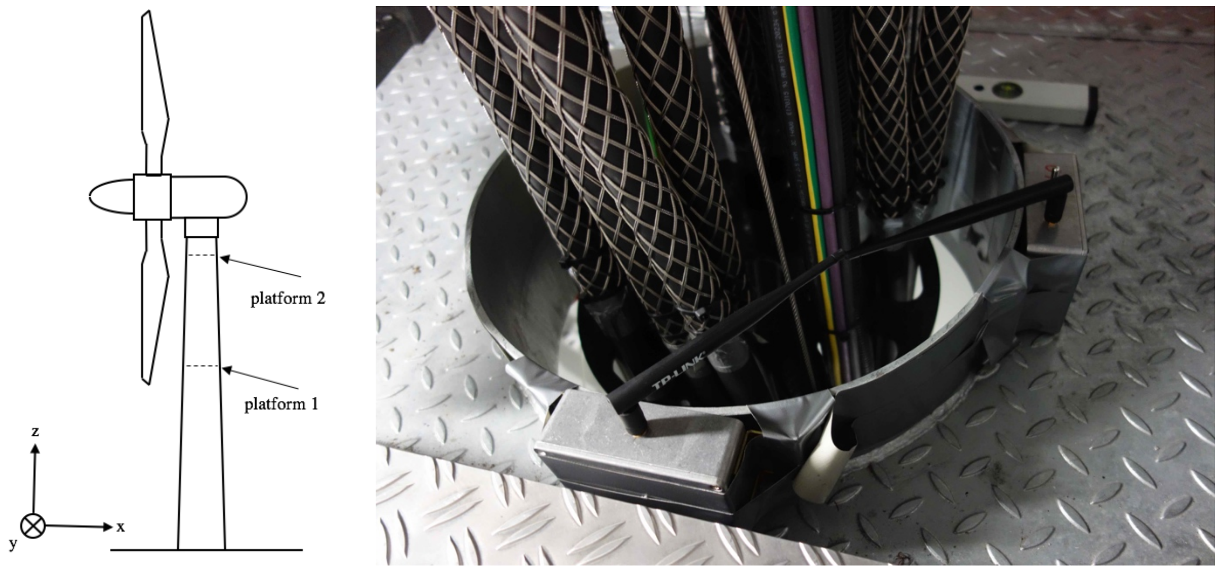

Figure 3. Sketch of mounting platforms (a) and wireless sensor nodes installed at platform 2 (b)

The sensors were set to record at a sampling rate of 12.5 Hz, using a 10 bit i.e. 1024 points analog-digital-converter (ADC). The recordable acceleration range was set to +/- 2g, resulting in a resolution of 1 mg (approx. 0.01 m/s^2) least significant bit (LSB) and a noise level of 550 $\mu g/\sqrt{Hz}$. The automatic conversion of time series data into frequency domain by Fast Fourier transformation (FFT) was enabled. Compression of data on the chip and radio transmission of the results only was selected to enhance the lifetime of the utilized Lithium batteries in the sensor node housings. To limit the size of transmitted data, only the 5 recorded frequencies with highest measured accelerations were recorded, displayed and stored. The present sensor node firmware offers either transmission of time series acceleration data, i.e. 1024 acceleration measurements within the sampling period when ADC is set to 10 bits, or conversion of this data into frequencies and their magnitudes and transmission of this compressed data only, or alternatively transmission of both time and frequency data. Calculation of additional key figures, such as RMS, mean value or maximum acceleration, is not enabled in the present firmware version.

Installation of the measurement equipment was performed during a planned inspection period with the wind turbine operation stopped and wind speed from 0 to 8 m/s, as derived from the SCADA system. For several hours in the sensor node measurement period, the rotor was in a parking position and excitation from wind was low. At night, the wind turbine was set to standard operation again, but stopped at the next morning to continue with intended inspection of the turbine. At the end of the second day the recordings were stopped and the measurement equipment was removed.

7. Preliminary results

First measurement data point towards eigenfrequencies of the tower in the sub-Hertz regime. Frequencies measured by the wireless sensors were between 0 and 0.4 Hz, most of them in the range of 0 to 0.1 Hz, some close to 0.3 Hz, as shown in figure 4 and figure 5. Especially sensor node 305018 on platform 2 recorded vibrations close to the frequency of 0.3 Hz approximately 8 hours and 18 hours after start of measurement campaign (noon on 31.05.). This corresponds well with the SCADA data, showing wind velocities of approximately 6 m/s on May 31st at 9 to 10 PM and approximately 8 m/s on June 1st at 6 to 8 AM.

The frequencies in the band of 0 to 0.1Hz are very low and seem to be unlikely. The reason might be the low signal-to-noise ratio of the measured acceleration or even acceleration values below the resolution capability of the wireless sensor nodes. Acceleration recordings by the wire-based sensors indicated values below 0.1 m/s^2 (i.e. 10 mg), sometimes even below 0.05 m/s^2 at days with low wind speed. The frequencies next to 0.3 Hz are close to the expected first eigenfrequency of 0.27 Hz, which was measured by the wire-based sensors and also fits to the design calculation.

Previous tests of the wireless sensor nodes on a pendulum with significant acceleration and a comparison of the recorded frequency by recordings from a laser vibrometer showed a good accordance [18]. Another explanation would be the influence of the conversion software to calculate FFT peaks from the raw data. Using more sophisticated filtering techniques and combining several sets of measurement data of the raw signal might lead to improved frequency measurements. Future tests at the wind turbine will also record raw data, which will be analyzed by external software programs and be used as input also for modal analysis. Further tests at the wind turbine during periods of higher wind speed are necessary to achieve a better signal-to-noise ratio and results closer to the eigenfrequencies measured by the wire-based measurement sensors. The recording and analysis of raw data might lead to improved understanding.

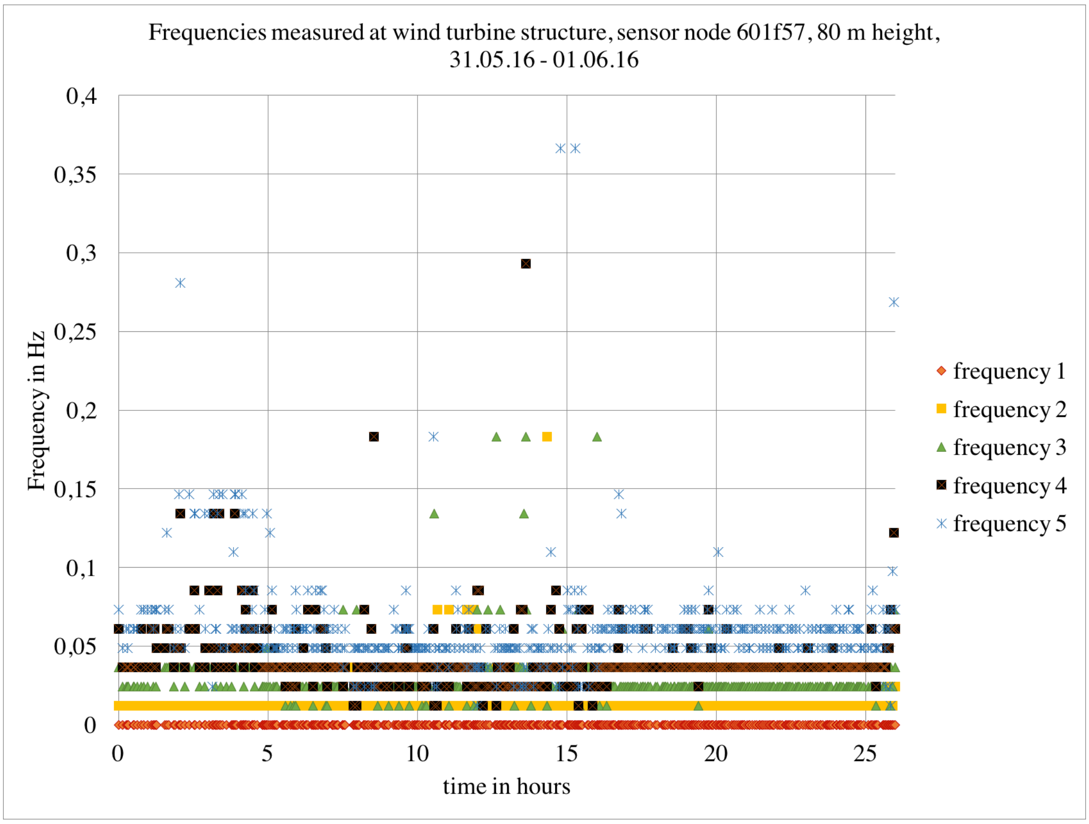

Figure 4. Frequencies measured at wind turbine structure by sensor node 601f57 on platform 1, 80 m above ground (five frequencies with highest amplitude)

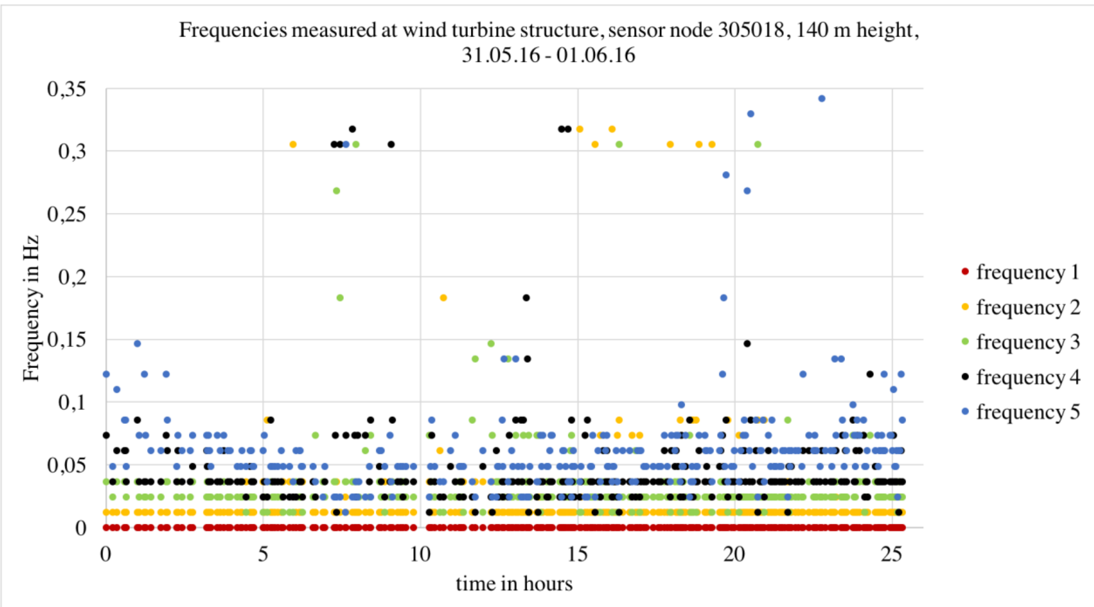

Figure 5. Frequencies measured at wind turbine tower by sensor node 305018 on platform 2, 140 m above ground (five frequencies with highest amplitude)

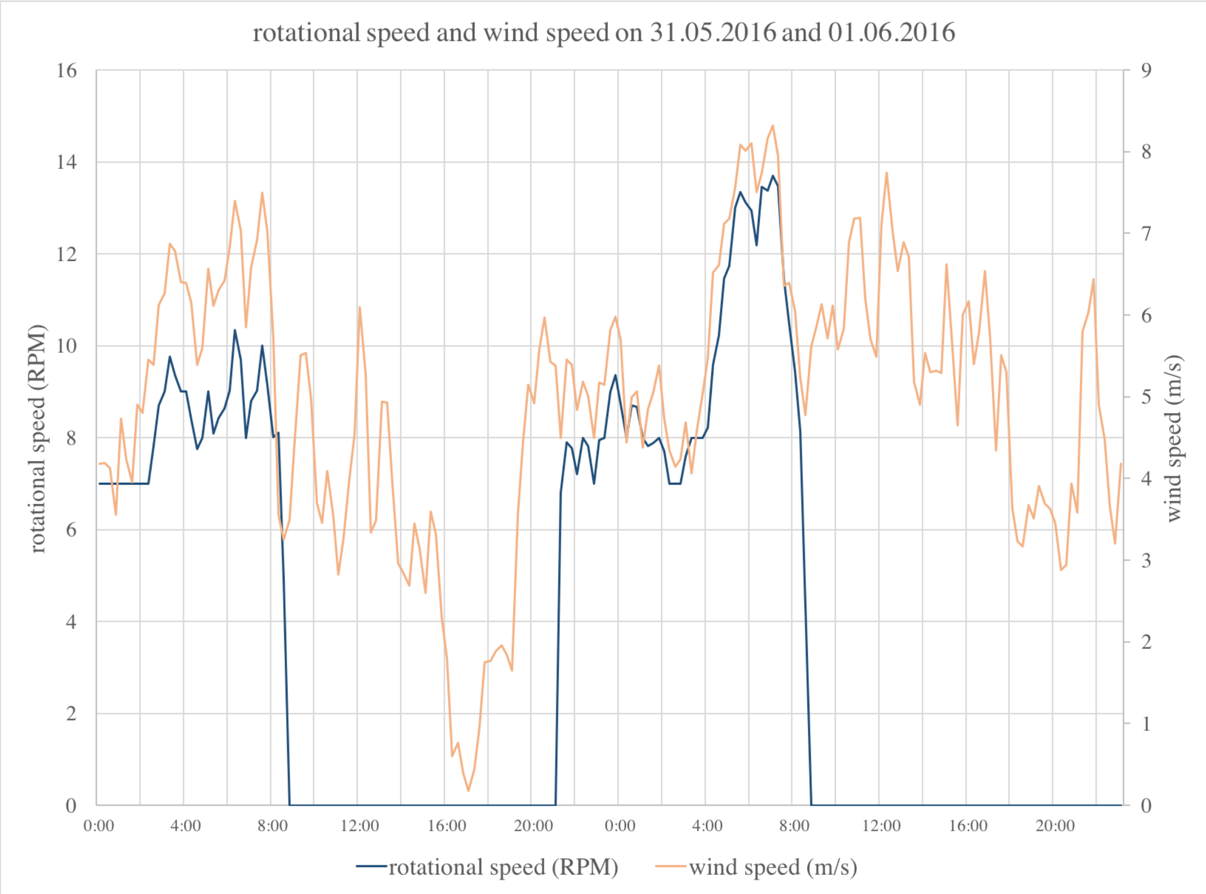

Figure 6. Rotational speed and wind speed measured on 31.05.16 and 01.06.16

8. Conclusions

Wireless acceleration sensor nodes can provide a cost-efficient, effective and sufficiently accurate method for wind turbine structural health monitoring. Comparing the overall costs for the structural health monitoring system and the benefit of an extended service lifetime for the turbine points towards a short amortization period. At this project, both wireless and wire-based sensors were utilized, but the costs for one wireless sensor (less than 300 Euro) was one order of magnitude lower than the costs for one wire-based sensor. A further development of the wireless sensor software will enable 3D acceleration recording instead of the one-dimensional (1D) recording. Subsequently, either the amount of measured data will be tripled at constant number of sensor nodes or the amount of sensors can be reduced by a factor of three at constant amount of recorded data. The optimum number of wireless sensor nodes per wind turbine still has to be determined. Whether ten, twenty or only five nodes are sufficient to record all necessary data will be subject of this research project. Same holds true for the ideal data compressing software on the sensor board itself. Any reduction of radio transmission without losing valuable measurement data prolongs the battery lifetime and shortens the amortization period for the monitoring setup.

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