Monitoring of Wind Turbine Structures with Concrete-steel Hybrid-tower Design

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Abstract
This research deals with setting up a monitoring system for the support structure of a 3 MW, onshore wind turbine of concrete-steel hybrid-tower design. Its purpose is to monitor structural dynamics and material strains to detect defects and fatigue and to determine the remaining service life of the wind turbine's support structure.

A literature search is conducted to find a suitable sensor configuration. Based on these findings, an adapted data acquisition system is designed and specific sensors are chosen. The monitoring system's design focuses on reliability, because the designated operating time is at least 2.5 years. Remote control and automated data synchronization techniques are therefore implemented.

The first version of the monitoring system comprises two accelerometers, one seismometer, and two temperature sensors installed on different tower levels. Data processing and preliminary results such as eigenfrequencies and tower displacement calculated from accelerations are presented.

Keywords: wind-turbine structure, hybrid tower, experimental vibration analysis, structural dynamics, proof of concept (SHM in action), lifetime management

1. INTRODUCTION
The overall objective of wind energy research is to reduce energy costs. One promising, resource-efficient approach is enhancing wind turbines’ service life, which is now generally 20 years [1]. According to estimations by [2], extending wind turbines’ service lives up to 30 years might be possible. The issue is becoming more relevant, because in the coming years, many established turbines worldwide are going to reach the end of their designed service life [3].

The support structure of wind turbines consisting of tower and foundation is of special interest in this context as it is one of the most expensive parts. Its failure rate is relatively low [4], but replacement is much more complex and expensive than it is for any of the other components.

In recent years, tower heights have increased to exploit low-wind-speed, onshore sites. To reach these heights while avoiding transportation issues and reducing costs, a new tower design called hybrid-tower design featuring of a concrete and a steel part has been developed.

Techniques for determining and extending the remaining service life of wind-turbine support structures are being developed in the context of a research project called MISTRALWIND, “Monitoring and Inspection of Structures At Large Wind Turbines”. The project started in August 2015 and will last for three years. One of its approaches involves developing a monitoring system to detect fatigue loads. Field experiments are being conducted at a full sized test turbine with concrete-steel hybrid-tower design.
In the first phase, a sophisticated monitoring system is being installed at the test turbine to characterize its structural dynamic and material behavior. Based on these findings, an adapted, cost-efficient measurement system (minimal number of sensors and low installation costs) is being developed in the second phase. This paper deals mainly with setting up the first measurement system and presenting preliminary results.

2. TEST WIND TURBINE

The test wind turbine shown in Figure 1b is located in south Germany. Its site is classified as IEC wind class 3A. The 3-bladed, direct-drive Siemens wind turbine has a 113 m rotor diameter and a rated power of 3 MW. The support structure was built by Max Boegl. Their tower design consists of a lower concrete part with prestressed elements and reinforcement and an upper steel part. The lower part, made of prefabricated concrete elements, reaches a height of 80 m. With the steel part, connected by a flange, the tower enables a hub height of 140 m. The tower houses four maintenance platforms as indicated in Figure 1a. The wind turbine was first operated in May 2015.

![Figure 1: Test wind turbine. a) Sketch with platform-positions. b) Photograph](image)

3. MONITORING-SYSTEM DESIGN: SENSOR CONFIGURATION

A literature search was conducted based on [5] before designing and installing a proper monitoring system. The former focused on monitoring systems employed for wind-turbine support structures to gather information about the selection and placement of sensors (where to install which type of sensor). The specific application case was taken account of in the process. This features:

- hybrid-tower design,
- fatigue detection, and
- high durability for a designated operation time of at least 2.5 years.

Figure 2 presents one of the literature search's results: a sensor configuration involving a small number of sensors. This configuration will be discussed below.
Vibration measurements can capture a structure's structural dynamics. The first and second tower bending modes for tall wind turbine towers are similar to the corresponding order cantilever bending modes [6]. The same results from operational modal analysis for various types of wind turbines can be found in [7], [8], [9], [10] and from shock hammer testing in [11].

The top of a wind-turbine tower is the ideal position for an accelerometer, because the tower's first-order bending mode has an antinode of vibration there. The tower's second-order bending mode however has a node of vibration at this point. Its antinode is located in the tower's mid-height area, where a second accelerometer should be positioned. A more accurate mode-shape estimation can generally be made if more accelerometers are available at different vertical positions on the tower. Highly sensitive seismic sensors can be used at ground level or on the foundation to detect the sum of transmitted vibrations.

The most common approach to detecting torsional modes involves two bidirectional accelerometers at the top of the tower, as in [7], [8], [9] for example. Another approach by [12] uses a fiber-optic gyroscope, which provides additional information.

Strain measurements allow more direct evaluation of material strain and stresses. They can be deployed as references for strain/stress calculations from model-based approaches and to monitor critical points directly, where large material strain and stresses are expected.

One critical point in the case of hybrid towers might be the connection between the tower's prestressed concrete and upper steel parts. As hybrid towers are relatively new to the market, long-term experience does not yet exist. The authors are thus unaware of any damage occurring at that point. On the other hand, steel wind-turbine towers connected to a concrete foundation have long been in operation. Connection damage has been reported in [13] and [14], and a combination of length and strain measurements is proposed to detect it. That measurement setup could also be used to monitor the concrete-steel connection in hybrid towers.

Tower displacement can be calculated, with certain limitations, from acceleration data [15], [16], or from rotation data [12]. It can also be measured directly—for example, by applying optical techniques such as photogrammetry or laser interferometry [17]. These methods are particularly suitable for short-term measurements, because installation at the wind turbine is unnecessary. (RTK-) GPS is another displacement-measurement technique
that has not yet been applied to wind turbines, but has been to a TV tower [18], [19]. The system that [18] uses achieves accuracies of up to 1 mm. Its application is only feasible atop of the nacelle as the receiver needs an unimpeded view of the sky.

4. MONITORING SYSTEM REALIZATION

In the previous chapter, type and desired positions of sensors have been specified. An adapted data acquisition system can be designed and specific sensors can be chosen based on those findings. The monitoring system's design focuses on implementing a reliable system. Further requirements are:

- high durability for a designated operation time of at least 2.5 years;
- resistance to environmental impacts;
- remote monitoring and control;
- precision: high time and value resolution;
- distributed, synchronized measurement channels;
- modular expandability: basis for future extension of measurement system and number of sensors;
- compatibility with wireless sensor systems; and
- simple installation.

Consequently, a wired, modular data acquisition system by Gantner Instruments was chosen and installed at the test wind turbine as depicted in Figure 3.

The DAQ system consists of a commander (Q.station) and up to 64 I/O modules (Q.bloxx) per controller. A bifilar bus that serves for data transfer and synchronization connects them. The system is controlled centrally through the commander. Various numbers of different I/O modules are available. For our first installation, we chose three A108 modules for vibration and temperature sensors and two A107 modules for strain gauges. Both modules enable a 24-bit analog-digital conversion at 10 kHz per channel. One of each was installed at the yaw platform and at the adapter platform. One A108 module was installed at ground level together with the Q.station.

For cabling between the measurement stations, an optical connection via glass-fiber cables was realized to prevent lightning damage. The system would allow the use of only one cable to connect all I/O modules. Redundant cabling was still laid to diminish the probability of total failure due to lead fracture.

The control and logger unit Q.station offers a broad range of configuration capabilities that help to establish a reliable monitoring system. It can be controlled via Ethernet and offers various interfaces for combination with different measurement systems: digital I/O, Ether-CAT, and CAN.

It is connected to a local PC with Internet access to enable remote system control. The PC runs various tools to supervise the system and guarantee data availability, preprocessing, and synchronization with a server. In case of communication errors between Q.station and PC, an email-notification is sent to authorized users.

The wind turbine's grid supplies power to the measurement system. The PC and Q.station are also connected to an uninterruptable power supply, which guarantees graceful PC shutdown to prevent errors in case of a power blackout. When power is restored, the PC performs an automatic restart requiring no user intervention. As a further advantage in case of power blackouts, up to two hours can be skipped and measurement data from ground level remains available.
Requirements for vibration sensors were determined with the help of the literature and previous short-term measurements at another wind turbine. Main requirements are high sensitivity and resolution, low noise, and a lower frequency-range limit of <0.2 Hz. The triaxial accelerometers (PCB 3713B112G) and the seismometer (Lennartz LE-3DLite-MkII) satisfied these requirements. In the seismometer's case, a correction function according to [20] was applied for low-frequency inputs. Preliminary tests were conducted to characterize the qualification of both sensors and data evaluation techniques for the task. A description can be found in [21].

Standard Pt100 thermocouples were deployed for temperature measurements. Due to complications during the first measurement campaign, strain sensors could not be installed. They were installed during a second campaign in June 2016, but data has not yet been evaluated. Therefore, this paper doesn't cover the strain gauges. Further sensors mentioned in chapter 3 will be installed during the course of the project.

Besides installation of the described measurement system, short-term measurements were conducted. Tower displacement was measured directly using laser interferometry. The results can serve as a reference for displacement calculations from accelerations. Furthermore, non-destructive testing methods such as radar, acoustic emission analysis, and ultrasonic testing were applied to the structure. Results will be presented in another publication.

The system was installed during two days in January 2016 and has been running continuously since March 2016.
5. DATA PROCESSING

Data preprocessing is the first data-handling step. As stated in the previous chapter, the DAQ modules sample at 10 kHz. The optical connection between the measurement stations allows a maximum baud rate of 1.5 MBd. This leads to a maximum sampling rate of 1250 Hz per channel for the overall system, which should suffice since, according to [22], wind-turbine vibration frequencies are generally between 0 Hz and 10 Hz.

The I/O modules always sample at 10 kHz and apply an anti-aliasing filter at 2 kHz. Using no further digital filtering, frequency components occur above 625 Hz. According to the Nyquist–Shannon sampling theorem, a 1250 Hz sampling rate results in aliasing effects. The data preprocessing procedure presented in Figure 4 is consequently applied.

The measured data is stored at a relatively high temporal resolution of 625 samples/s as some of the subsequent data-evaluation techniques entail significant data reduction.

The second data-processing step is operating-condition sorting, which can be done using data from the wind turbine's supervisory control and data acquisition (SCADA) system. The most important data sets relevant to structural dynamics are those characterizing power, rotational speed, and wind speed; however, additional data sets can also help to understand vibration behavior. Data from the SCADA system is available not only as 10-min-average values, but also at higher resolution featuring irregular time steps.

Only FFT has been applied so far to evaluate vibration in the frequency domain. The next step will be to implement the FDD technique according to [23] to perform modal identification.

Besides analysis in the frequency domain, a method for calculating displacement from acceleration data according to [15] and [16] was implemented in [24]. It is based on bandpass filtering and double integration as shown in Figure 5. Due to the use of the 4th order Newton-Cotes method for integration, data is reduced by ¼ per integration. One the method's drawbacks is that only the dynamic part of the displacement is detectable, because low-pass filtering of the data eliminates the static and low frequent part (frequencies below the first tower bending eigenfrequency). Data from RTK-GPS measurements could be used for data completion as the greatest accuracies are attained for low frequent vibrations [25].

Project partners have created a high-fidelity FEM model to combine measurement data from different sensor types.
6. PRELIMINARY RESULTS

One of the first results that can be obtained by looking at the raw data is that the measurement system is qualified for the task, as it generates data of high quality and availability. All three vibration sensors detect tower vibrations even in the wind turbine's idle state. The system has been running accurately for three months since March 2016. Data evaluation is still in progress while this paper is being written, so only preliminary results from the data processing described in the previous section will be presented. Figure 6 shows exemplary time-series data from vibration measurements at three different tower levels during wind turbine operation at rated power of 3 MW and rated rotor speed of 14 rpm. The data was generated on 11 Apr. 2016 at 01:00. The corresponding displacement data was calculated according to the previously described procedure and is depicted in Figure 7.

Typical vibration amplitude values during operation can be read from the figures. Amplitudes decrease with tower height, but phasing is nearly identical, which is distinctly visible from displacement data.

As a reference for displacement values calculated from velocity/acceleration data, direct displacement measurements were carried out during installation of the measurement system on 27 Jan. 2016 using a laser-Doppler vibrometer. During operation at rated power, a maximum displacement of 15 µm was measured at 1.6 m tower height. Maximum displacement during the exemplary time-series data from Figure 7 is 5 µm at ground level. In different data sets, it reaches as much as 12 µm. In both cases, it is of the same order of magnitude as direct measurement results. Synchronous measurements will be conducted for more precise comparison.
Results from frequency analysis show up to four dominant vibration frequencies occurring independently of rotor speed and can be identified throughout most data sets, which makes them eigenfrequencies of the wind turbine (tower). They are clearly visible in Figure 8, which shows the results of a FFT of seismometer data from the enhanced exemplary data of 11 Apr. 2016 at 01:00–02:00. During that time, the turbine was operating at rated power and a rotor speed of 14 rpm leading to a 1p excitation frequency of 0.233 Hz. Together with the 3p-frequency and its further harmonics up to 15p they can be easily identified in the spectrum. Eigenfrequencies and dominating exciting frequencies resulting from rotor rotation are distinguishable by their shape.
Figure 8: FFT spectrum of S1 seismometer data; wind turbine operating at rated power

To date, the eigenfrequencies listed in Table 1 can only partly be assigned to defined vibrational modes. \( f_1 \) corresponds to the first tower bending mode the frequency of which was calculated as part of the tower design process for a rigid foundation to be 0.27 Hz. \( f_2 \) is probably the 2nd tower bending eigenfrequency as it is more dominant in data from S2 than in that from S3. This makes sense, because the bending modes of wind turbines are similar to cantilever bending modes. \( f_3 \) and \( f_4 \) might be either higher tower bending, rotor, or coupled modes.

<table>
<thead>
<tr>
<th>Notation</th>
<th>Frequency in Hz</th>
</tr>
</thead>
<tbody>
<tr>
<td>( f_1 )</td>
<td>0.27</td>
</tr>
<tr>
<td>( f_2 )</td>
<td>1.08</td>
</tr>
<tr>
<td>( f_3 )</td>
<td>3.3</td>
</tr>
<tr>
<td>( f_4 )</td>
<td>5.5</td>
</tr>
</tbody>
</table>

Table 1: Eigenfrequencies of test wind turbine from FFT peak picking

The determination of mode shapes, damping, and the vibrational modes of higher dominant frequencies is currently under investigation. Project partners will use modal parameters as well as displacement values to fit an FEM model, which helps to evaluate material stresses.

7. CONCLUSION

A monitoring system for a 3 MW wind turbine of concrete-steel hybrid-tower design was developed, installed, and brought into service. The first version consists of three vibration and two temperature sensors. As it is a basis for further development and enhancement, modular expandability was focused on. An automated data-preprocessing system was designed to provide high quality data for further evaluation. Preliminary results from frequency analysis reveal the first two tower bending eigenfrequencies to be at \( f_1 = 0.27 \text{ Hz} \) and \( f_2 = 1.08 \text{ Hz} \). All three vibration sensors detect the
first eigenfrequency in the wind turbine's operational and idle states. It matches the value calculated during tower design. Operational modal analysis will be conducted to obtain further modal parameters. Dynamic tower displacement was calculated from acceleration/velocity leading to values of the same magnitude as reference measurements from laser-Doppler vibrometry. Further synchronous measurements are planned for verification.

The monitoring system will be enhanced: a larger number of accelerometers is being considered to obtain a more accurate mode shape determination. Wireless sensors are being tested to reach poorly accessible positions. Employment of an RTK-GPS device will be evaluated for displacement measurements. Length and strain measurements will be conducted to monitor the connection between concrete and steel. As a next step, strain gauges will be installed in proximity of the vibration sensors. Project partners will create an FEM model for data fusion and fatigue calculation.

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REFERENCES


