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Monitoring and Inspection Techniques Supporting a Digital Twin Concept in Civil Engineering

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ABSTRACT

The use of data from non-destructive inspections and from monitoring to accompany the life cycle of buildings and structures is relatively new to civil engineering. Such an approach can be beneficial for a stakeholder in many ways since it helps to schedule maintenance and rehabilitation events in an efficient way, to reduce repair time and effort and to estimate the remaining service life of a structure. It will finally increase the overall performance and sustainability of such structures.

The paper will review the challenges and chances of sensing techniques in the frame of a digital twin concept. An example obtained from former research mainly done in the MistralWind project will demonstrate the possibilities of modern sensing techniques applied to a wind turbine.

INTRODUCTION

There are different ways to use beneficially data from inspection and monitoring of constructions obtained during the design and construction phase as well as during the whole lifetime. In the digital world, several techniques were established to support individual parts of the design and construction process. For decades, techniques like Computer Aided Design (CAD) and Finite Element Modeling (FEM) were used to support the construction engineer. Developments in the last decade including sensing techniques and Internet of Things paved the way to a more holistic treatment of how we deal with constructions. This includes a process called Building Information Modeling (BIM) that was developed in particular for the construction industry. Another method called Digital Twin (DT) or eventually Digital Clone and primarily developed to evaluate processes in mechanical engineering provide a full digital representation of a construction based on CAD or FE models and being updated by sensor data.

Following similar requirements, DT concepts were successfully established in mechanical engineering decades ago. In civil engineering, holistic life-cycle assessment techniques were established much later. One reason might be that the overall lifetime of structures in civil engineering is much longer than typically in mechanical engineering applications. A bridge or a tower is designed for a lifetime of hundred or more years. A digital twin concept including monitoring must be designed for such a long lifetime or able to be established beneficially at an existing structure with a possibly unknown impact history. Most civil engineering structures are composed from a mix of different materials (steel, concrete, coatings, polymers, wood, fibers). Very often, the composition is unknown or the real quantities not well documented. Concerning the actual condition of a structure, mostly guessing is done based on visual inspections at given fixed intervals. Moreover were sensing techniques in civil engineering not highly developed making it difficult to gather data from a structure under harsh environmental conditions. In the last few decades there is a significant improvement observable concerning all mentioned aspects. Numerical simulations became more accurate, computing power is increased and cost-efficient sensing techniques are available. The awareness of the public regarding performance and sustainability of civil engineering structures increased and even under economic (and not only ecologic) prerequisites inspection and structural health monitoring is accepted as a valuable tool.

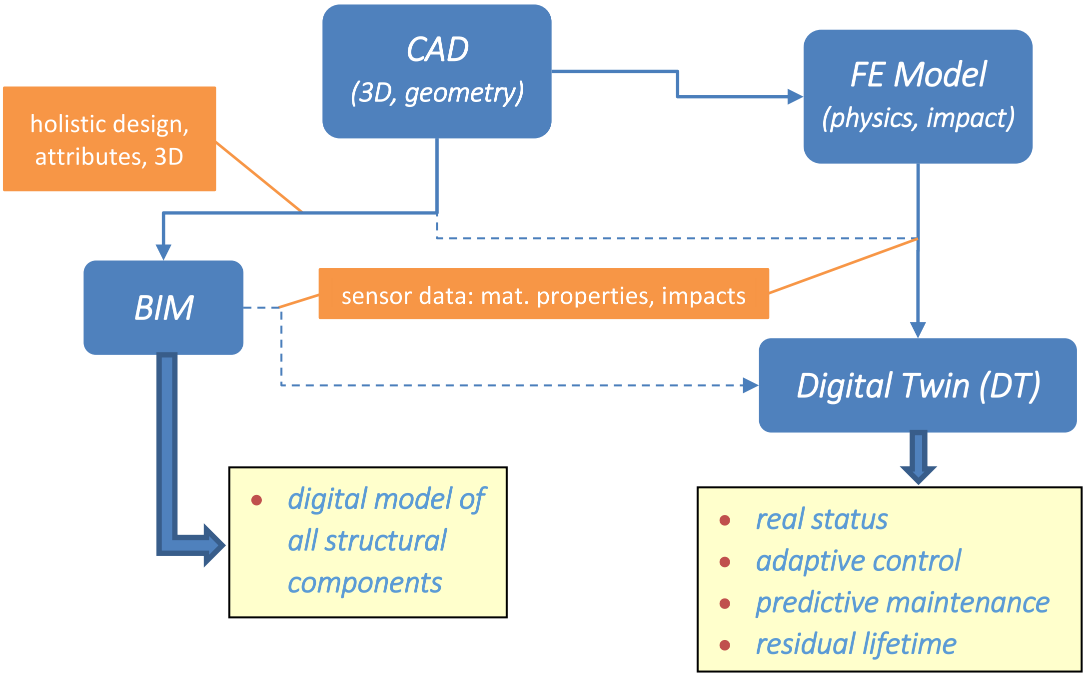

Fig. 1. CAD and Finite Element Modeling as a basis for a BIM and Digital Twin concept

BUILDING INFORMATION MODELING VS. DIGITAL TWIN

Per definition, a Digital Twin (DT) is a digital representation (i.e. replica) of a real structure like a bridge or a tower using a model and being updated in real-time or near-real-time by data from sensors to establish a valid representation of this real structure.

A DT can consist primarily on a CAD or a FE model (Fig. 1). Sensor data from inspections or monitoring add information about the material properties, impacts and deteriorations to the twin. In most cases, an existing FE model is used as a basis for DT but eventually also a BIM model can serve. Most applications reported about DTs in the literature are using FE models.

There are similarities between DT and Building Information Modeling concepts. BIM primarily brings together topics from different subsections and maintenance groups dealing with the same construction starting right away from the design phase and including digital information obtained during construction [Borrmann et al. 2018]. All information is put together in the three-dimensional building information model. This makes it much easier for the architects and civil engineers to work together in a more holistic manner. It establishes also a good basis for further reconstructions, maintenance, repair and rehabilitation.

FURTHER BENEFITS AND ISSUES OF A DIGITAL TWIN

Summarizing, a Digital Twin is a full digital representation of the actual condition of a structure using data obtained from inspections and monitoring. The data are used to generate valuable insights into the structure that is suffering from impacts, fatigue and deterioration processes. A DT can accompany the whole lifetime while the model is updated whenever new physical data from the structure are available. Representing such a structure in the most comprehensive way, all aspects of the material (including composition and deteriorations) on the micro-, meso- and macro-level should be known. Such a comprehensive model is time-consuming to be established and can be inefficient depending on the required Level of Detail (LoD). The required LoD should be defined prior to establish any DT concept at a construction since it governs for example the number, spacing and type of sensors.

Another critical point concerning bearing structures is the interaction with loads and the reaction of the structure on excitations and displacements during operation. Without any information about such impacts, a model can deviate from reality quite far. Information should include measured data obtained from singular or repetitive non-destructive inspections and from continuous performance monitoring.

Predictive maintenance and life-cycle assessment

If meaningful digital data are provided by a monitoring device over time in a periodic way (e.g. by sensing techniques and automated data analysis) the model can be updated in a way that the optimal date for maintenance can be predicted as well as the most effective way to perform maintenance. Such a “predictive maintenance” can reduce maintenance efforts making them more cost-efficient compared to manual inspection at certain fixed intervals. Furthermore, it is helpful being able to use the data for a prediction of the residual service life. This could help solving budget and schedule issues and help planning rehabilitation or – in case of wind turbines – repowering.

Combination of sensors and optimal sensor placement

The number of sensor information obtained from different regions of a structure is crucial. It is obvious that data from different physical sensors and all relevant structural components should be used to establish a valid model of properties and deteriorations. Sensor combinations are also necessary to discriminate between normal and abnormal behavior of a structure. Due to natural differences in the ambient temperature, structural components can expand or shrink what could lead to relatively high values of strain measured by strain gauges or fiber optical sensors.

The “best” place to collect data from a structure should not rely on guessing and experience only. Based on the numerical model sensor placement algorithms can be used to determine the best locations under given constraints (costs, accessibility etc.). Such algorithms can derive the optimal placement calculating and weighting the contribution of the data of a certain sensor to the model. An example for the application of optimal sensor placement algorithms at the wind turbine project described below can be found in Neri [2017].

Adaptive control

The time interval between the measurements and therefore the period between model updates governs certainly the precision of the model. However, there is another feature related to this. Considering structures with properties that can be controlled (i.e. changed) throughout operation, sensor data can be used to optimize the control. Such structures can be for example buildings (high-rise buildings) with active damping elements or adaptive shapes, bridges with adaptive anchors and supports or constructions with integrated machines or generators. While most structures today are non-adaptive, wind turbines are highly dynamic and adaptive concerning energy harvesting from wind.

INSPECTION AND MONITORING OF WIND TURBINES

Wind turbines are remarkable structures in many ways since they bring together concepts from electrical, civil and mechanical engineering. They are optimized to harvest electrical energy from wind having a machinery part (generator with rotor) located in the nacelle and they are supported by a tower based on a foundation. Materials used vary a lot and consist typically of steel for the tower and/or nacelle, steel-reinforced concrete (SRC) for the basement, pre-stressed concrete for the tower, wood and fiber-reinforced polymers using glass (GFRP) or carbon (CFRP) fibers for the rotor (Fig. 2). A large variety of individual or combined materials and composites are used in practice. Inspection and maintenance of the individual parts is usually done separately. This could be inefficient and time consuming. Compared to the many different climatic and geographic regions where they are operated, the design does not vary much, no matter if they are located on-shore, off-shore in a hilly or forested area or in an icy or hot-dry area. While some turbines are operated as an individual construction, many are grouped together to a “wind farm” offering additional options for monitoring and adaptive control.

Fig. 2. Schematic of a wind turbine consisting of a material mix of steel, steel-reinforced concrete (SRC), concrete, glass or carbon fiber reinforced polymers

The most efficient way to monitor such a structure is to do so over the whole life-cycle. This begins in the design and construction phase by recording the real composition and properties of the materials and components and by transferring the data into a full digital structural model. Such a procedure is more efficient because it brings together information already existing but separately compiles. The same model can be used as a basis for a Finite Element Analysis of loads and structural deformations. After the assessment the interaction between the components and the environmental conditions (temperature and humidity, wind, vibrations) have to be recorded during operation along with the operational data (rotations, harvested energy etc.). If enough sensor information are available, the measured data can be used to identify structural changes and deterioration. Wind turbines are structures subjected to high dynamical loads in respect to rotations but also internal vibrations. Several million load cycles can occur during the lifetime of such a structure and they are typically designed for a total service life of twenty years no matter of their location [Botz et al. 2016, Loraux 2017, Geiss 2019]. Inspections can be time-consuming and cost-intense concerning the location (off-shore) and the height of the structure. Most parts are considered individually and very often inspected by different specialists and companies in intervals of two or four years. A holistic management concept considering all parts of a wind turbine is in its infancies [Geiss & Grosse 2018].

Inspection nowadays is typically done with the naked eye and basic inspection tools but a variety of non-destructive techniques is available and they more and more used.

Selection criteria depend mainly on the component and material under consideration. For the rotor blades, ultrasound and infrared thermography [Jüngert et al. 2009] is most often used. For a nacelle video-endoscopy or ultrasound cold be used and for concrete towers and foundations inspections based on RADAR or impact-echo are suitable. Most modern wind turbines are equipped with a few integrated sensors delivering data to the Supervisory Control and Data Acquisition (SCADA) system. Typically, such a system includes sensors for the electrical components and some for wind speed and wind direction measured on top of the nacelle. Different more sophisticated monitoring devices can enhance this approach. Rotor blades can be monitored using fiber-optical sensors (FOS) or accelerometers while for the tower vibrations typically strain gauges, accelerometers or seismometers are used. FOS systems can be used to automatically control the pitch angle of the blades [Schmidt 2018] to optimize the overall energy harvesting, what is a good example of adaptive control [Barlas & van Kuik 2010].

Different monitoring devices and concepts for wind turbine components were tested during the MistralWind project and some results will be presented in the following. MistralWind is an acronym for the "Monitoring and Inspection of Structures at Large Wind Turbines" focussing on the estimation of the remaining service life of wind turbine support structures using information from inspections and structural health monitoring and comparing them to a FE analysis. The following descriptions will illustrate the statements above being the basis for a Digital Twin. They are based on former publications [Botz et al. 2017a, Geiss et al. 2017, Wondra et al. 2019] and on another one that will be published later in 2019 [Botz et al. 2019]. Most of the work was done by these authors, industrial partners several students and – concerning the FE modelling – by colleagues from the Chair of Structural Analysis of TU Munich [Emiroglu 2019].

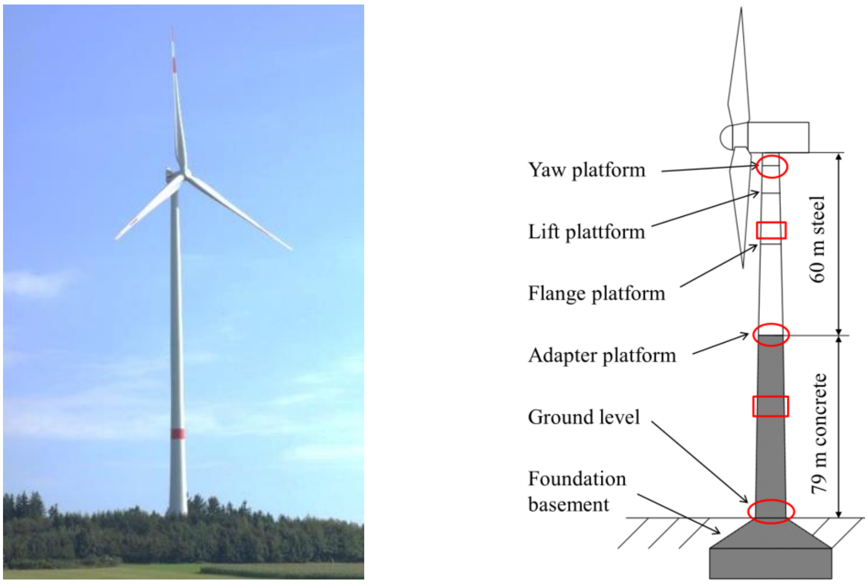

Fig. 3. Wind turbine monitored in the MistralWind project (left) and sensor positions marked in red (right)

MONITORING OF STRUCTURAL COMPONENTS OF A WIND TURBINE

In the MistralWind project, a direct-drive 3 MW wind turbine manufactured by Siemens AG equipped with a rotor of 113 m diameter (Fig. 3 left) was investigated over many months. The turbine is located in a forested area in Northern Bavaria. The support structure consists of a steel-reinforced foundation carrying a hybrid tower (Bögl et al. 2016) made of prefabricated, prestressed concrete elements (height 0-79 m) and an upper steel part (height 79 - 139 m). Fig. 3 (right) indicates the individual parts of the wind turbine and depicts locations of sensors described in the following sections.

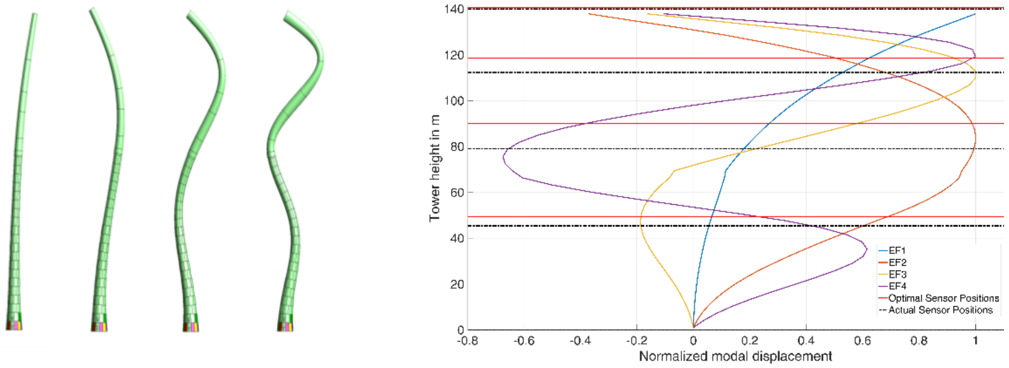

Fig. 4. Shapes of the first four eigenmodes derived from the FE model (left) and calculation is the optimal sensor placement to identify these modes(right) [Neri 2017]

Several sensor systems have been evaluated during the project including optical, wired and wireless sensors. The wired data acquisition systems were initially installed at heights of 0 m (ground level), 78 m (intersection between pre-stressed concrete segments and steel tower) and 137 m (nacelle). A study of the optimal sensor placement was performed by Neri [2017] to identify the best sensor locations concerning eigen-vibrations and the first four eigenmodes based on the FE model (Fig. 4 left) and an analytical beam model. Several algorithms including *Heuristic Visual Inspection*, *Effective Independence Method*, *Kinetic Energy-based Method*, *Genetic Algorithm*s and *Artificial Bee Colony Algorithms* [Sun et al. 2013] have been tested. The latter performed best for the considered structure. It was confirmed that the three locations circled in Fig. 3 (right) are good choices but it was suggested to enhance them by two more locations at the squared locations in Fig. 3 (right) at 46 m and 113 m height. All following evaluations are based on sensor data from all five locations.

Optical monitoring systems

Over a short period a video capture system was applied tracking the two dimensional motion of the tower structure. This was done to test cost-efficient vibration monitoring systems that can be used at structures without access to the inner parts. The video was taken with a frame rate of 25 fps using either a Canon 1100D or 1300D reflex camera equipped with a telephoto lens (Fig. 5 left). Given that the relevant vibrational frequencies of the tower are limited to values below 6 Hz, a sufficient sampling rate can be presumed. The focal length of the telephoto lens was set to 650 mm and the luminous intensity was therefore 1:8. A heavy tripod was used to suppress any mechanical oscillations of the camera that might be caused by wind turbulence. Since the video recording mode was used to capture the tower motion, a resolution of 1280*720 pixels was achieved. Using a h264-avc1 compression method, time slots of 30 min video data were captured. To ensure a sufficient contrast in the video, a small part of the tower at the top of the concrete section (Fig. 5 upper right) was selected to be observed. Thus, no markers at the structure itself had to be used and no illumination was required. The video data was stored in the internal camera memory and processed subsequent to the measurements using algorithms obtained from digital image correlation (DIC) techniques. The scaling factor was derived via photogrammetric measurements. The optically measured vibrations (Fig. 5 lower right) can be compared to data obtained from accelerometers installed inside of the turbine what was done over a period of several hours. Only little variations in the recorded vibrations and no significant deviation concerning the determination of fundamental eigen-frequencies were observed. For a short period of time, the optical measurement system was enhanced by out-of-plane measurements using a Laser-Doppler Vibrometer.

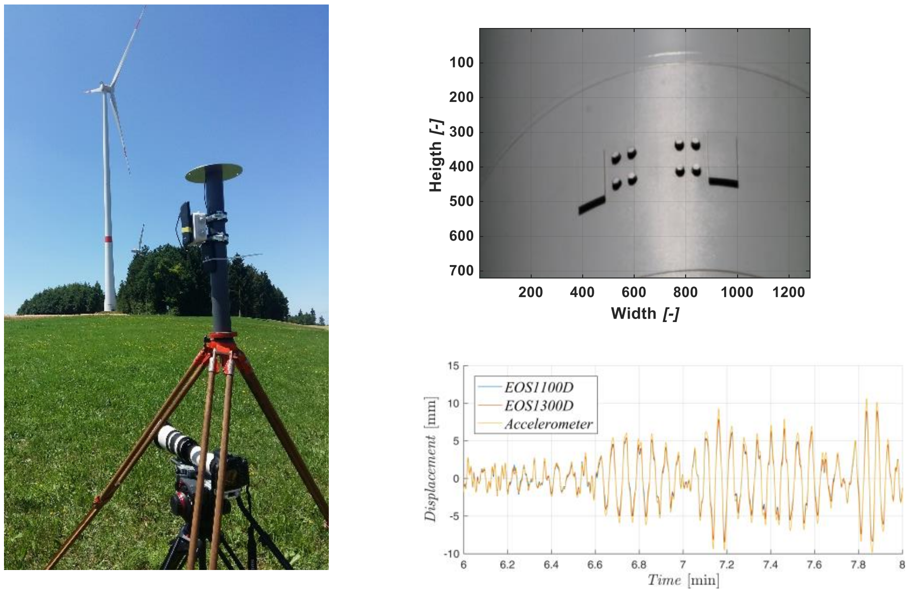

Fig. 5. Optical monitoring system (left), section of the wind turbine used for vibration measurements (upper right) and according displacement data from optical monitoring system compared to accelerometer measurements of the stationary in-turbine monitoring system (lower right) [Mayer 2017]

Wired sensor systems

A 24-Bit analog to digital conversion system at a sampling rate of 625 Hz was used for the wired sensing system along with a set of triaxial accelerometers (Fig. 6 left and middle) installed inside the turbine. This system was expanded by 3D seismometers (Fig. 6 right), fiber optical sensors of the Bragg grating type, strain gauges and thermocouples.

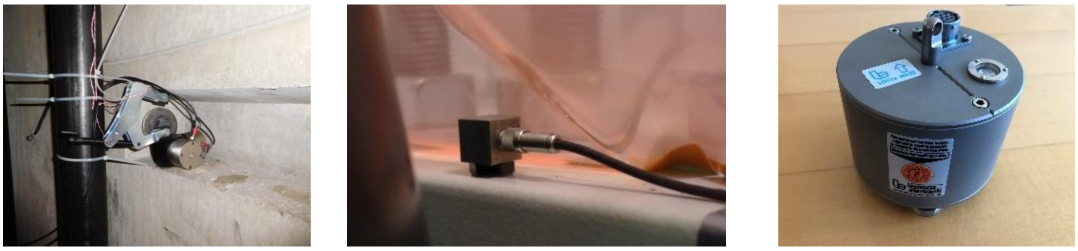

Fig. 6. Triaxial accelerometers and seismometer (right) used for monitoring

Wireless sensor systems

Wireless acceleration measurement systems are beneficial since they can operate independently from electric power and data transmission cables giving more flexibility to structural health monitoring. Therefore, a MEMS-based wireless acceleration system consisting of sensor nodes of the "Neomote" type was applied and tested. Neomote devices from Metronome Systems (Fig. 7) were further developed together with scientists from the University of California in Berkeley [Wondra et al. 2019].

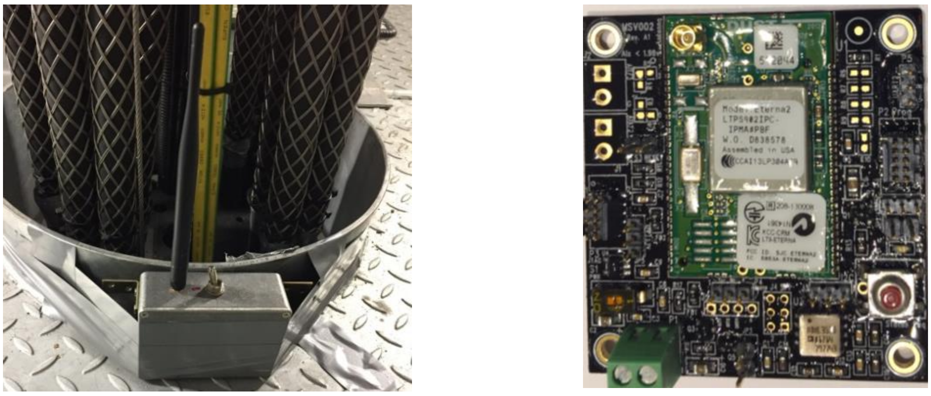

Fig. 7. Wireless acceleration sensor node installed at yaw platform in 138 m height (left) and mote layout (right) [Wondra et al. 2019]

Numerical simulation

The numerical evaluation of loads and fatigue using a finite element simulation requires detailed information about the geometry of the tower components and the materials used. Combined stress states could arise. While simplified models are often facilitated for system control algorithms due to their computational efficiency, their application in fatigue behavior is limited. On the other hand, modeling of each detail would cause an immense computational complexity. In the MistralWind project, a finite element model was developed (Fig. 8) by colleagues from the Chair of Structural Analysis of TU Munich [Emiroglu 2019] based on the construction plans and built reducing the tower wall consistently to its mid-plane [Botz et al. 2017a].

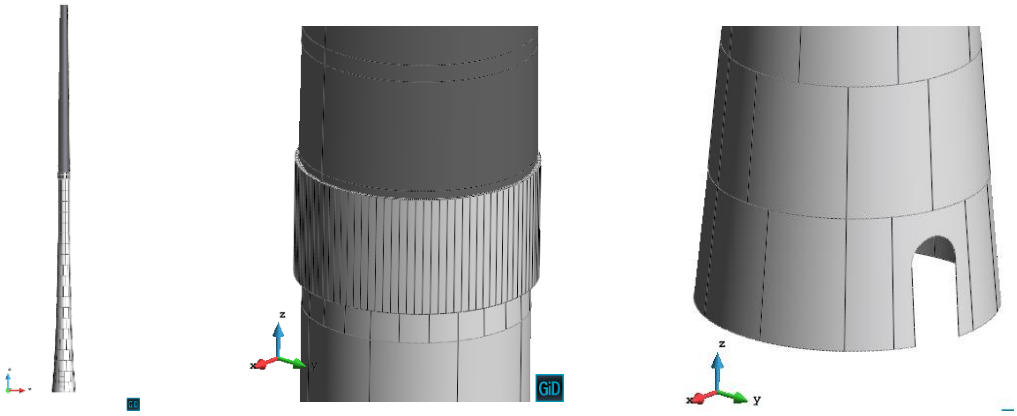

Fig. 8. Some details of the CAD model developed by the TUM Chair of Structural Analysis [Botz et al. 2017a]

The model assumes a linear relation between stresses and strains with a St. Venant-Kirchhoff material law. It is assumed that the initial static loading has a prominent effect on the dynamic behavior while the loading in the dynamic phase does not affect the structural stiffness properties significantly. The analysis of the tower considered the geometrical nonlinearities, which occur due to the initial displacements resulting from the pseudo-static loading from self-weight and pre-stressing effects. This is achieved by utilizing the nonlinear Green-Lagrange strains in the static analysis phase and the dynamic phase is assumed to be linearizable around the found static equilibrium. Thus, the updated tangent stiffness matrix at the static equilibrium is used for the dynamic and the eigenfrequency analysis (Fig. 4 left). It was observed that the initial displacements and the prestresses could cause a shift in the computed eigenfrequencies of the tower compared to the conventional eigenfrequency analysis [Emiroglu 2019]. The explained procedure yields a more accurate computation of the eigenfrequencies compared to the experimental data, as can be seen from Tab. 2.

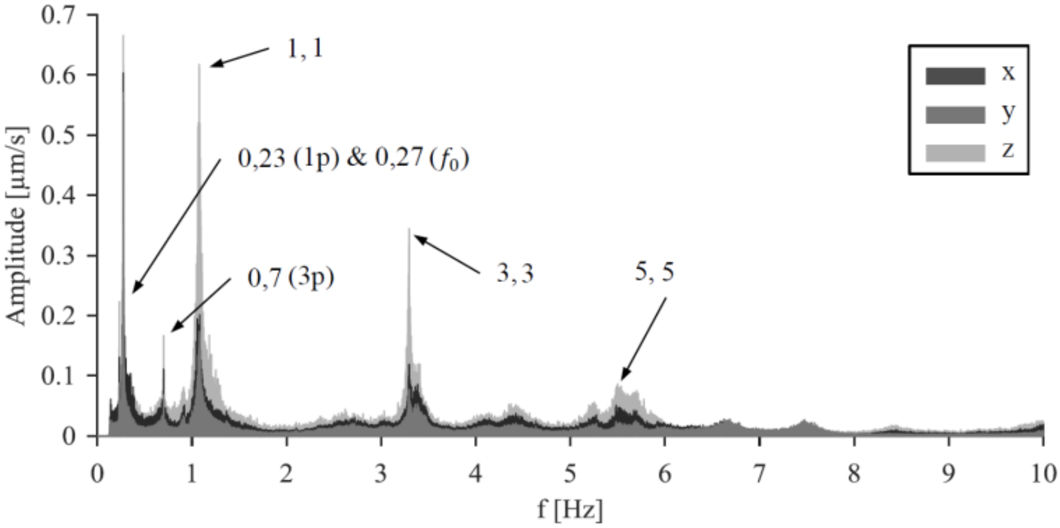

Fig. 9. Spectrum of vibration data acquired by seismometer placed at tower base during 24 h comprising idle and operational state (adapted from Oberländer [2016])

Data Analysis

At the time being, some of the above-mentioned sensing systems have been running continuously for more than three years. The overall data quality is typically between good and very good and enabled for a detailed investigation of structural integrity and behaviour due to wind load. After installation of the monitoring system, the first step in the analysis was to transform vibration data into the frequency domain to determine possible eigen-frequencies of the tower of the wind turbine. Fig. 9 shows a spectrum of vibration data from 24 h, acquired by the seismometer placed at the tower base.

In the 24-hour period displayed in Fig. 9, the turbine was in idle and operational state. Consequently, excitation- and eigen-frequencies can be determined. The dominant excitation frequencies are the 1p and 3p frequencies. 1p is the excitation frequency based on the number of revolutions of the rotor taken in one second corresponding to the nominal rotor speed of 14 rpm = 0.23 Hz and caused by rotor imbalance. 3p is the excitation frequency caused by the tower shadow affecting all three blades. The first bending eigen-frequency f_0, known from design calculations, and three further dominant frequencies (as correlating to Fig. 4 left) are detected. Considering their mode shapes generated by the FE analysis and an Operational Modal Analysis (OPA, see below) they were identified as higher order bending eigenfrequencies. The results of the spectral analysis are outlined in Tab. 1.

Tab. 1. Excitation- and eigen-frequencies obtained by analysis of seismometer data:

measured frequencies	Interpretation using FE analysis and OPA
0.23 Hz	1p excitation from rotor imbalance at 14 rpm
0.27 Hz	1st bending eigenfrequency
0,70 Hz	3p excitation from tower shadow at 14 rpm
1.1 Hz	2nd bending eigenfrequency
3.3 Hz	3rd bending eigenfrequency
5.5 Hz	4th bending eigenfrequency

The actual structural dynamic behavior of the wind turbine is characterized by pairs of closely spaced bending modes of the tower in rotor plane (side-side direction, SS) and perpendicular (fore-aft direction, FA) due to deviations in rotational symmetry induced mainly by the nacelle mass distribution [Chauhan et al. 2011]. These individual modes cannot be properly discriminated by a simple peak picking in the frequency domain. The accuracy of the determined eigen-frequencies is consequently limited. A transformation of vibration signals from tower-fixed to nacelle-fixed coordinate system is conducted using yaw angle data from the SCADA system and Operational Modal Analysis is applied to identify these modes.

Operational Modal Analysis

Operational Modal Analysis (OMA) is a technique to link the recorded vibration data to eigenmodes of a structure. Unlike classical modal analysis no artificial excitation is needed, the generic excitation forces during operation or idling are sufficient and no information about the excitation force is needed. Different OMA methods are described in the literature. The presented data analysis used the Covariance Driven Stochastic Subspace Identification (SSI-COV) technique as described in Botz et al. [2017b]. They reported that it showed fast and stable results for applications in the MistralWind project. The basic concept of the method is to create a large number of parametric state space models based on the vibration data. The results are visualized in stabilization diagrams, in which the poles (possible eigenmodes) of the state space systems are displayed with corresponding frequency and model order. The modal parameters can be extracted from the system matrices of these models as described in Rainieri & Fabbrocino [2014]. The input parameters for SSI were chosen following the methods described by Devriendt et al. [2014].

Botz et al. [2017b] have compiled stabilization diagrams for MistralWind data sets recorded 25.12.2017, where the wind turbine was in idle mode and in operational mode, but only idle mode data are shown here. The chosen OMA techniques allowed for an evaluation of data from several simultaneously acquired sensor data. In this case, acceleration data acquired during ten minutes at height positions 0 m, 78 m and 137 m were recorded, each in two directions. This enabled for a more accurate eigen-frequency determination. Fig. 10 shows the corresponding stabilization diagram.

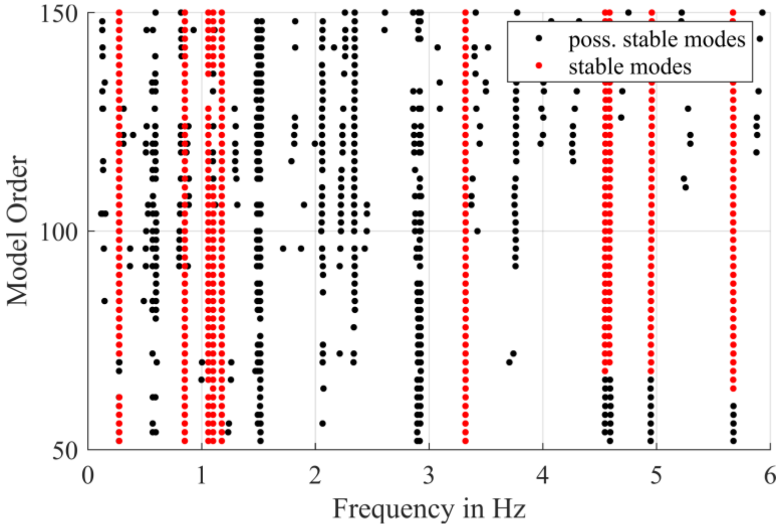

Fig. 10. Stabilization diagram to determine the eigenmodes of the wind turbine in idle state from acceleration data

As expected, for each bending mode identified by peak picking in the signal spectrum, actually two close bending modes in FA and SS direction were found (Tab. 2), except for the 4th bending mode. These modes were compared to the eigen-frequencies of the FE model as shown in the third column of Tab. 2. In the model, the nacelle is approximated as a point mass, so no closely spaced bending modes occur. For comparison the bending modes from OMA in FA-direction were considered, as the blades were in feathering position with smaller surface perpendicular to FA movement, causing less influence on the vibrations in FA-, than in SS-direction. The resulting modal parameters from OMA and FE model are shown in Tab. 2.

Tab. 2. Results of OMA and comparison of calculated and measured eigen-frequencies.

Eigen mode	**measured OMA frequency**	**measured OMA damping**	**original FE model**	**updated FE model**
	Hz	%	Hz	Hz
FA1	**0.274**	**0.27**	**0.281**	**0.273**
SS1	0.276	0.91		
FA2a	**1.058**	**0.35**	**1.152**	**1.138**
SS2	1.101	0.13		
FA2b	1.177	0.39		
SS3	3.320	0.70		
FA3	**3.400**	**1.66**	**3.220**	**3.207**
SS4	**5.674**	**0.26**	**5.508**	**5.495**

The original values obtained from numerical simulations appear to differ from the measurements what led to an adjustment in the masses and stiffness values in the model. The values of the updated model (Tab. 2 last column) are correlating much closer to the measurements with variation between 0.3 % and 6.6 % only. In this case, the delta between measured and simulated data is based on an inaccurate model. However, the same technique of model updating would work also for occurring deteriorations leading to a shift of eigen-frequencies.

From accelerometer data, it is possible to refer to the actual movement of the structure at different heights [Harhaus 2018]. For the particle motion data shown in Fig. 11, a bandpass filter was applied to limit the motion to the bending mode of the first eigen-frequency at ground level (left) and yaw platform (right).

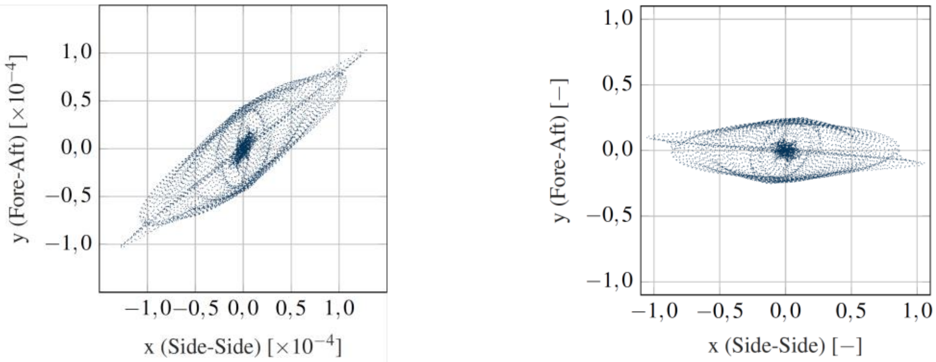

Figure 11. Particle motion diagrams obtained from accelerometer measurements at two different heights [Harhaus 2018]

Such data can reveal the directivity of motions what is relevant to determine the mode of vibration but also misalignments of the sensors or malfunctions can be recognized early. However, a misalignment alone would have no influence on the determination of eigen-frequencies using an Operational Modal Analysis.

Procedures for calculating displacements from acceleration data performed in the time domain and based on filtering and integration have been developed Botz et al. [2017b]. In addition, displacements were calculated using data from the optical monitoring system described above. These data from independent measurement systems (two cameras at different positions and one accelerometer of the stationary monitoring system; Fig. 5) are correlating well. Based on this validation, the general functionality of both methods as well as their applicability to field measurements at wind turbines and civil engineering structures was shown. The two measuring techniques – or better the combination of both – can be used to further improve the FE model and to establish a Digital Twin. Based on model updates the residual service life of the wind turbine can be recalculated.

CONCLUSIONS AND OUTLOOK

A full-digital model of a construction can be improved by physical sensor data obtained from the structure. Three ways to obtain data can be identified that should be combined: Assessment during or right after construction, inspections and monitoring. Such data enable for a Digital Twin that is a replica of the construction along with all physical aspects including deteriorations. A non-static model is updated whenever new information (data) is available.

Measuring accelerations at different locations on a wind turbine enables a determination of vibrational bending and torsional modes. The modal parameters can subsequently be obtained from Operational Modal Analysis and used to update the FE model of the wind turbine support structure. The availability of a validated FE model enables many applications. In the MistralWind project, it was used to determine hot spots and calculate material stresses at these locations for remaining useful life analysis.

Based on the identified modal parameters, the evolution of the first order bending mode during several maintenance events was linked to each individual work step. The frequency change was used to estimate rotor and generator mass employing a one degree of freedom mass spring model. For the rotor mass, an error of 4 % was found that approves the employed frequency values and method. The results were used to review the modal parameters of the FEM model for different nacelle masses [Botz et al. 2017a].

A structure such as a wind turbine can numerically be modelled along with the environmental parameters and the loads – such an approach is usually considered as a Digital Twin. During the lifetime of the structure the loads, impacts and fatigue will increase aging of the structure. These processes are typically non-linear, combined and difficult to be predicted. This results in deviations of the Digital Twin from reality. The procedures described above and being developed in the MistralWind project are fundamental footsteps towards a more reliable Digital Twin of the considered wind turbine. A continuously updated twin can help in scheduling maintenance more efficiently [Geiss & Grosse 2018] and extending the overall service life of the structure.

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