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# A Measurement and Signal Processing Concept for the Dynamic Analysis of Operating Wind Turbines

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ABSTRACT — *The life time of a wind turbine is mainly influenced by its dynamics. In order to avoid resonances in the variable speed range of a wind turbine, resonant frequencies of the entire turbine including substructure resonant frequencies as well as harmonic excitations have to be known accurately. Whereas the harmonic excitation frequencies are multiples of the rotational speed and well known, resonant frequencies have to be either calculated using a proper simulation model or identified experimentally. A verification of calculated results by a measurement is the preferable approach. So the extensive knowledge and the deep understanding of the dynamics of a wind turbine allows the precise prediction of its behaviour. This contribution presents modal testing of a 3 MW wind turbine on a 100 m tubular tower with a 120.6 m rotor developed by W2E Wind to Energy GmbH. The research is a part of the* DYNAWIND *project of the University of Rostock and W2E funded by the German Federal Ministry of Economic Affairs and Energy. This research mainly focuses on the application of operational modal analysis techniques to an industrial wind turbine. Specific problems are addressed, and hints for modal testing on wind turbines are given. Furthermore, an effective measurement setup including deformation measurement of rotor blades is proposed for identification of the modal parameters of a wind turbine. Finally a comparison of the multibody simulation results with respect to the measurement results is given.*

## 1 Introduction

The life time of a wind turbine is mainly influenced by its dynamics. In order to avoid resonances in the variable speed range of a wind turbine, resonant frequencies of the entire turbine including substructure resonant frequencies as well as harmonic excitations must be known accurately. Whereas the harmonic excitation frequencies are multiples of the rotational speed and well known, resonant frequencies have to be either calculated using a proper simulation model or identified experimentally. A verification of calculated results by a measurement is the preferable approach. So the extensive knowledge and the deep understanding of the dynamics of a wind turbine allows the precise prediction of its behaviour.

The wind turbine this study is based on is the W2E-120/3fc wind turbine, designed by W2E Wind to Energy. It is a horizontal axis wind turbine (HAWT) with three blades. The prototype of the wind turbine has a rotor diameter of 120 m and a nominal power of 3 MW, so it is suitable for low wind speed sites. The wind turbine is equipped with an innovative drive train consisting of Winergy's HybridDrive and W2E's LarusCompact drive train concept. The HybridDrive combines a two stage planetary gearbox with a permanent magnet synchronous generator (PMSG). It is a medium-speed generator controlled by three full converter systems. Due to the full converter systems the wind turbine is independent of the grid frequency. A CAD sketch of the wind turbine is shown in Figure 1.

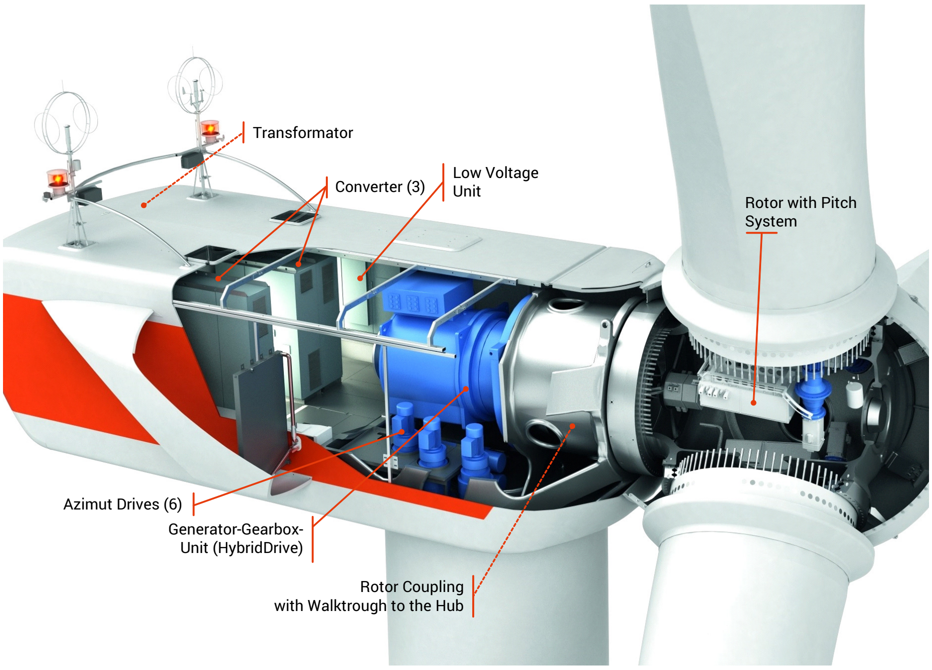


Fig. 1: CAD sketch of the W2E-120/3fc (3 MW wind turbine)

The wind turbine has been developed by W2E Wind to Energy during the years 2010 to 2013. In 2013 a prototype of that wind turbine has been manufactured and erected on a 100 m tubular tower in Mecklenburg-Western Pomerania. The prototype of the 3 MW wind turbine is shown in Figure 2.

The research is a part of the DYNAWIND project of the University of Rostock and W2E funded by the German Federal Ministry of Economic Affairs and Energy. This contribution mainly focuses on the application of operational modal analysis (OMA) techniques to an industrial wind turbine. An extensive introduction to OMA techniques is given in [1]. Specific problems are addressed, and hints for modal testing on wind turbines are given. Furthermore, an effective measurement setup including deformation measurement of rotor blades is proposed for identification of the modal parameters of a wind turbine. The measurement procedures evolved from the experience of different measurement campaigns on a 2 MW wind turbine presented in [2] and [3], while the knowledge on the dynamic behaviour of wind turbines has been gained from detailed multibody simulations [4].

## 2 Measurement Concept

A special measurement setup for modal testing has been proposed within this research work. The focus has been placed on the transfer of the measurement signals from the rotor to the nacelle and the type of sensors used for deformation measurement of the blades. For the modal testing of the blades it is necessary to use sensors which are able to measure low frequency ranges below 1 Hz on the one hand and a large measurement range of $\pm 2$ g on the other hand. Based on this requirements Inertial Measurement Units (IMU) from PEPPERL+FUCHS are used for dynamic analysis of the blades. IMUs have the advantage that translational acceleration and angular velocity can be measured at the same time representing a six-dimensional sensor.

Overall ten IMUs are placed on the wind turbine, eight in the blades, one in the nacelle and one in the tower. While one blade (Blade 2) has been equipped with four IMUs at 5 m, 14 m, 22 m, and 28 m, the other two blades (Blade 1 and 3) are equipped with two sensors at 5 m and 28 m. A scheme of the position of the IMUs is shown in Fig. 3. Here S*xx* represents the the different sensors. The communication between sensors in the blade and the data acquisition system from IMC Test & Measurement GmbH, Germany, in the nacelle is realised by CAN bus and signal transmission by a slipring.

Fig. 2: Prototype of the W2E-120/3fc (3 MW wind turbine) erected in Kankel, Mecklenburg-Western Pomerania, September 2013

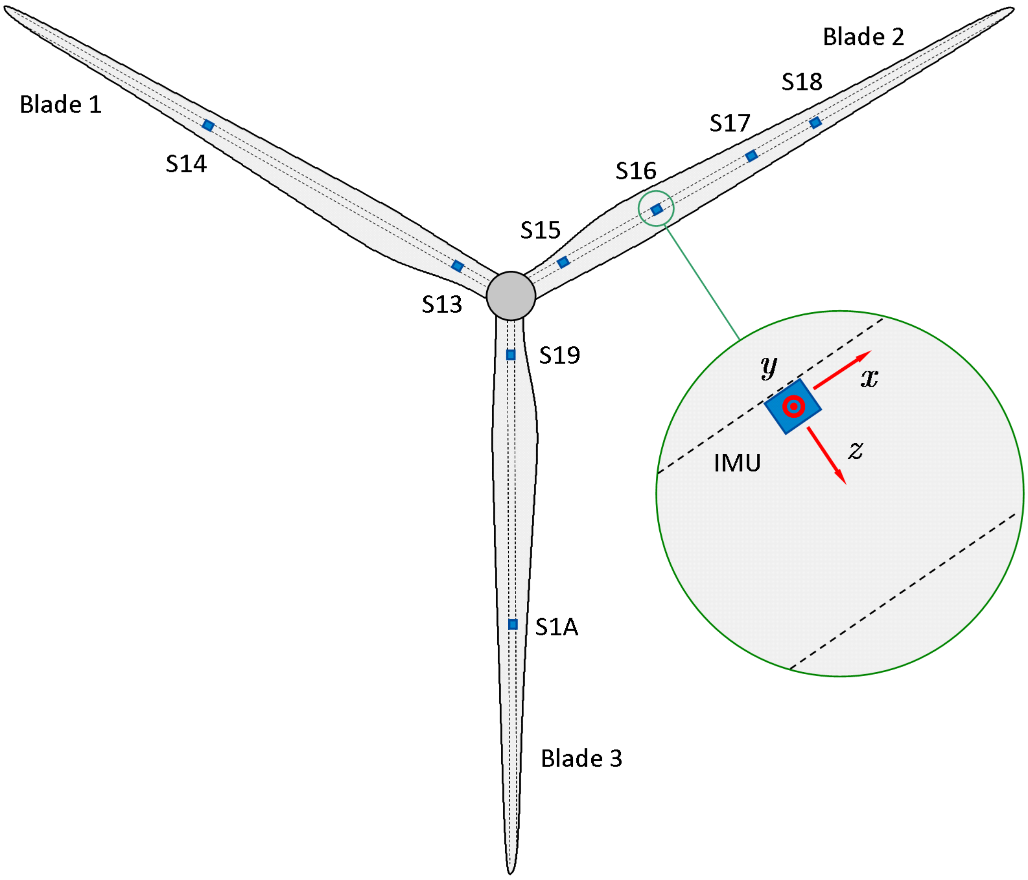


Fig. 3: Placement of Inertial Measurement Units IMUs (S$xx$) in the Rotor Blades of the Wind Turbine

The IMUs are mounted to the rear spar of the blades because of the planar mounting surface, see Fig. 4. The IMU is oriented with the x-axis pointing to the blade tip and the z-axis pointing to the leading edge of the blade. So the y-axis points against to the wind direction if the blade is pitched to zero degree.

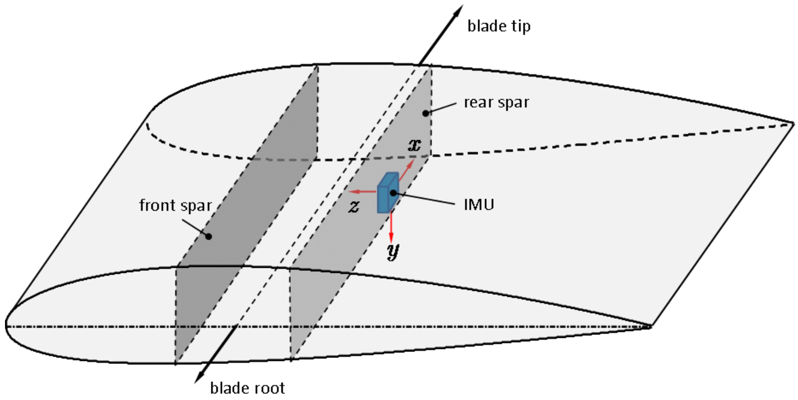


Fig. 4: Position of a Inertial Measurement Unit (IMU) in the Cross Sectional Area of the Wind Turbine

Finally two IMUs, S11 and S12 as shown in Fig. 5, are placed in the nacelle next to the yaw bearing and at tower top, respectively. In addition to the 60 signals provided by the IMUs seven steering signals from the Programmable Logic Controller (PLC) of the wind turbine are recorded by the IMC system. The signals comprise the pitch angle of the blades, the wind speed obtained by the anemometer on the nacelle, the electrical power, the rotor position, the angular velocities of rotor and generator, and finally the yaw angle.

A second data acquisition system from BRUEL & KJÆR has been positioned at the elevator platform. Eight piezoelectric (P*xx*) accelerometers from PCB are positioned in the tower at tower of 16.5 m, 31.5 m, 49.5 m, and 70.5 m in two perpendicular directions (Fig. 5). The elevator shaft has been used for positioning of the sensors with respect to the nacelle orientation. In addition three accelerometers are positioned at the rear of the main frame in the three orthogonal directions. For synchronisation of the two data acquisition systems the rotor position is also recorded by the BRUEL & KJÆR system. Two more accelerometers positioned at the mainframe next to the yaw bearing in fore-aft and side-side direction are also used for synchronisation of both measurement data.

The ten IMUs and 13 accelerometers deliver 73 measurement signals. Considering the signals used for synchronisation 71 signals are usable for the dynamic analysis. In combination with the seven operating condition states of the wind turbine a dense measurement grid for dynamic analysis of the operating wind turbine is obtained. The overall measurement concept is shown in Fig. 6.

## 3 Measurement Campaigns

Three different measurement campaigns have been carried out to investigate the overall dynamic behaviour of the wind turbine. The aim of the different measurement campaigns is to estimate the dynamical behaviour within different operating states of the wind turbine.

As a reference measurement first the wind turbine has been investigated in parked position. The azimuth drives have been locked to keep the wind turbine in a fixed direction. The rotor has been positioned, but not locked, with Blade 2 pointing vertically downwards. The blades were pitched to feathered position to keep the rotor in an idling state. Unlike the measurement campaign on the 2 MW wind turbine where the rotor was locked [3] the dynamic reference of the non-rotating wind turbine is obtained. Within this measurement campaign the full measurement setup comprised both data acquisition systems according to Fig. 6. The measurement time has been chosen to two hours.

In a second measurement campaign the dynamic behaviour of the wind turbine in power production was estimated with wind conditions above rated. The azimut drives have been again locked to keep the wind turbine in a fixed direction. For power production the rotor rotates under pitch control. Compared to the previous reference

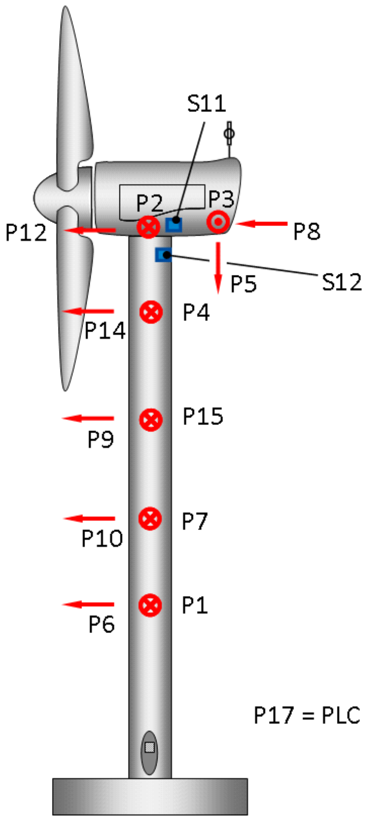


Fig. 5: Position and Directions of Piezoelectric Accelerometers (P*xx*) and Inertial Measurement Units IMUs (S*xx*) at Tower and Nacelle of the Wind Turbine

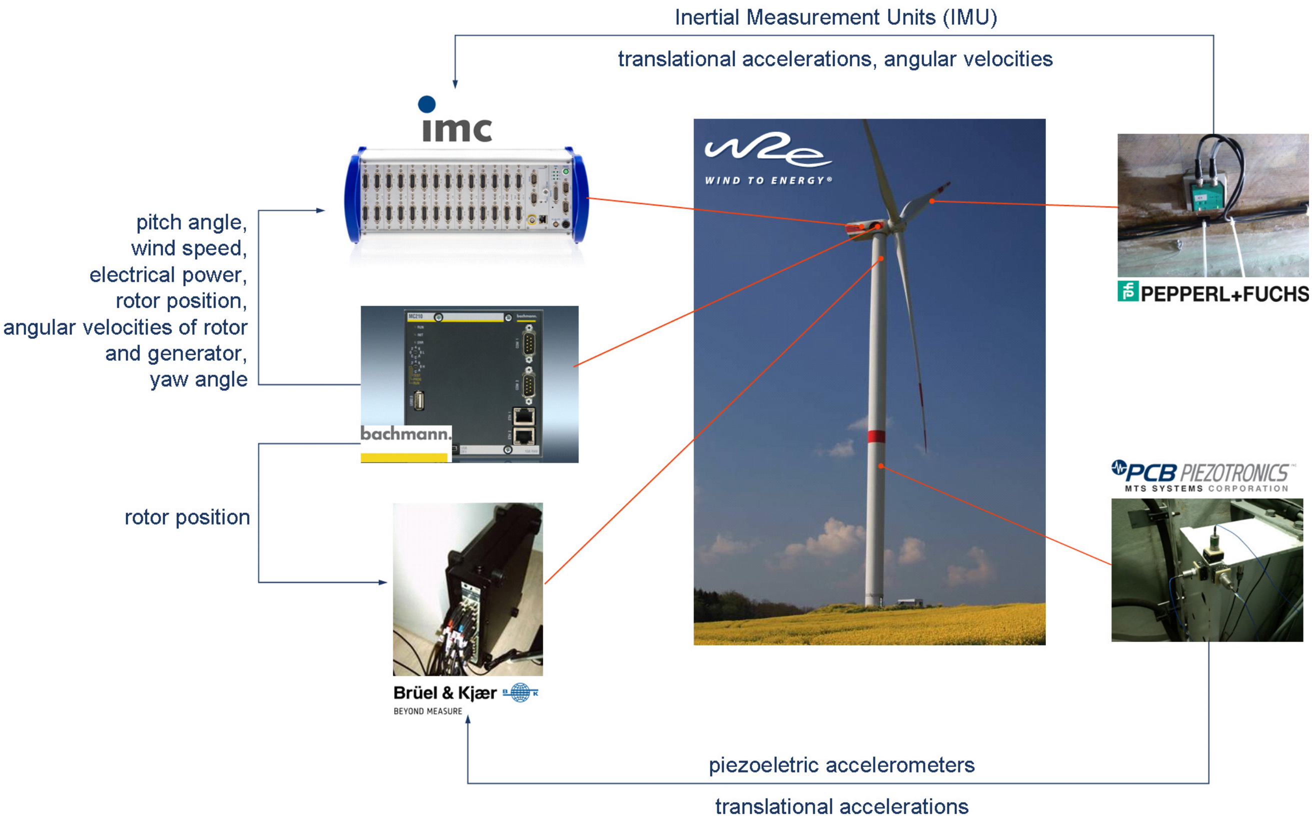


Fig. 6: Measurement Concept for the Dynamic Analysis of Operating Wind Turbines

measurement resonances due to forced excitation are taken into account. The full measurement setup with both data acquisition systems according to Fig. 6 has been used again within this campaign. This also holds for the two hour time interval for measurement.

Finally a long-term measurement campaign over a period of two months has been carried out using the IMUs and the IMC data acquisition system only. The aim of this long-term campaign has been to measure the dynamic behaviour of the wind turbine considering different operational states. The measurement data have been recorded directly to a flash memory on the IMC system. The IMC system allows a remote control for data transfer and administration. For technical reasons the BRUEL & KJÆR system does not enable such a long-term measurement leading to the restriction to the IMUs only.

# 4 Signal Processing and Measurement Evaluation

The evaluation of the measurement data has been carried out with two different methods. First the detailed measurements on Blade 2 are analysed during different operating states. Then the entire measurement data of both data acquisition systems have been evaluated to obtain the overall dynamic behaviour of the wind turbine.

## 4.1 Signal Processing for the Blade

The Inertial Measurement Unit IMU360D-F99 from PEPPERL+FUCHS combines a triaxial acceleration sensor and a triaxial gyroscope. It is a microelectromechanical system (MEMS), where the sensor is placed on a chip. This type of sensor is called strapdown IMU, where the acceleration sensor and the gyroscope are rigidly mounted on the moving body whose motion is measured. The orientation of the body and by this its linear acceleration in spatially fixed directions is obtained by a fusion algorithm combining accelerometer and gyroscope data. MEMS are able to measure accelerations and angular velocities with a frequency of 0 Hz, enabling for example to measure the gravity vector. Instead piezoelectric accelerometers have a low pass characteristic and are not sensitive below a lower cut-off frequency.

One of the main advantages of an IMU for our application is that the torsion of a deformable body can be measured by a single gyroscope. As shown in Fig. 3 and 4 four IMUs are placed along the rear spar of Blade 2. For the evaluation of the measurement data in form of visible mode shapes the translational and rotational measurement data are processed at the acceleration level. Therefore the measured angular velocity vector $\boldsymbol{\omega}(t)$ has to be differentiated with respect to time. This is done in the frequency domain using Fast Fourier Transformation (FFT),

$$\boldsymbol{\Omega}(\mathrm{i}\bar{\omega}) = \mathscr{F}\left(\boldsymbol{\omega}(t)\right), \tag{1}$$

with the Fourier transform $\boldsymbol{\Omega}$ of the angular velocity vector $\boldsymbol{\omega}(t)$, the angular frequency $\bar{\omega}$ and $\mathrm{i}^2 = -1$. The angular acceleration vector $\dot{\boldsymbol{\omega}}(t)$ is then obtained by

$$\dot{\boldsymbol{\omega}}(t) = \mathscr{F}^{-1}\left(\boldsymbol{\Omega}(\mathrm{i}\bar{\omega})\,\mathrm{i}\bar{\omega}\right). \tag{2}$$

The angular acceleration vector from (2) is used to calculate a linear acceleration $\boldsymbol{a}_2$ of any arbitrary point with a distance vector $\boldsymbol{r}_{21}$ from the measurement point by the rigid body kinematics (Fig. 7),

$$\boldsymbol{a}_2 = \boldsymbol{a}_1 + \dot{\boldsymbol{\omega}} \times \boldsymbol{r}_{21} + \boldsymbol{\omega} \times (\boldsymbol{\omega} \times \boldsymbol{r}_{21}), \tag{3}$$

where $\boldsymbol{a}_1$ is the measured linear acceleration vector at the measurement point of the IMU.

This scheme has been applied to six points around the measurement point of the IMU, see Fig. 8. From this evaluation scheme a visualisation method of the mode shapes is obtained, where six virtual linear acceleration measurement points with three independent directions each around the real measurement point of the IMU are obtained. This results for the four IMU along the blade axis in 12 real and 72 virtual measurement signals used for modal analysis. Note that the virtual measurement points behaves like a rigid body only neglecting local vibrations of the blade structure within the measurement volume defined by the six virtual measurement points. .

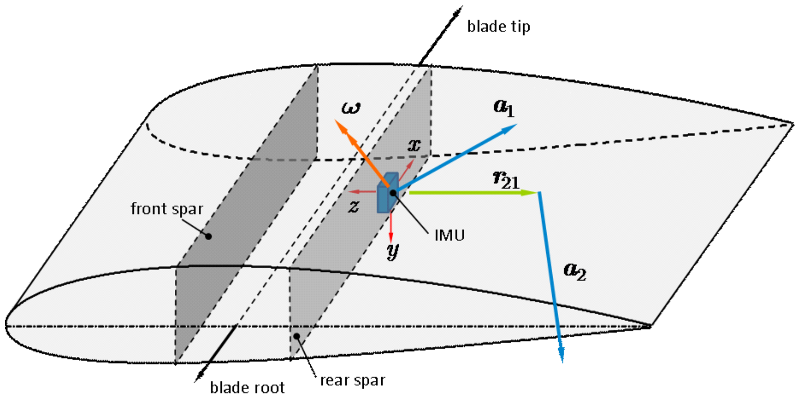


Fig. 7: Scheme of the transformation of the angular degrees of freedom of the IMUs

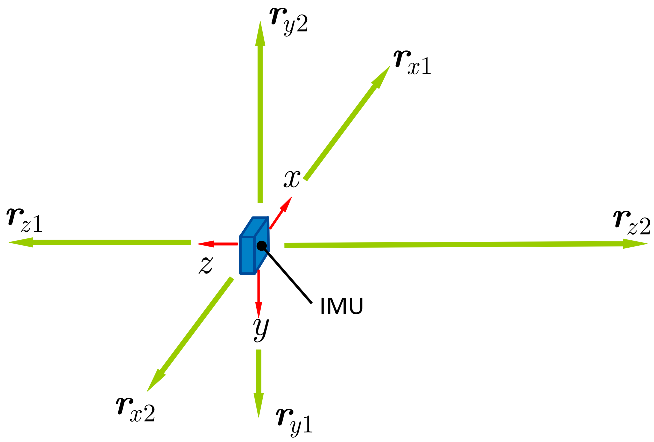


Fig. 8: Virtual measurement points obtained from rigid body kinematics

### 4.2 Signal Processing for the entire Wind Turbine

The modal analysis of the entire wind turbine faces some other challenges compared to the signal processing of the blade. The main problems was the synchronisation of the two independent data acquisition systems and the different dynamic properties of the sensors. The synchronisation has been reached on the one hand by recording the rotor position with both data acquisition systems and on the other hand by the evaluation of measurement signals from the IMU S11 and the piezoelectric accelerometers P2 and P12, see Fig. 5. The measurement data of of the two data acquisition systems are merged together and synchronised using FAMOS from IMC.

To reproduce the same dynamic behaviour as can be observed from the piezoelectric accelerometer data a 0.7 Hz high pass filter is applied to the IMU data. Furthermore a 10 Hz low pass filter is applied to both data acquisition systems circumventing aliasing effects. Then the step size of both measurement data sets is also synchronised. Furthermore some kinematic transformations are applied to the measurement data. In particular the tower measurement data have to be transformed with respect to the yaw angle.

It has to be pointed out that the linear accelerations of the IMUs have been taken into account only. The main reason is a simplification of the evaluation of the measurement data. Furthermore the effect of the blade torsion is assumed to be small compared to blade and tower bending for global modal analysis.

## 5 Measurement Results and Comparison to Multibody Simulation

The modes have been extracted using operational modal analysis (OMA) techniques by ARTeMIS Modal Pro 5.1. The built-up of the multibody model of the 3 MW wind turbine follows the principles of [4], [5], [6], and [7].

## 5.1 Modal Analysis of the parked Wind Turbine

According to measurement campaign on the 2 MW wind turbine [3] the dynamic analysis on the 3 MW wind turbine starts with a parked configuration as a starting point for further investigations in different operating states. During this measurements the blades have been pitched to feathered position, and the rotor has been brought to Y-position with Blade 2 pointing downwards in front of the tower. Numerous modes have been identified, while exemplary five of them are listed in Table 1. The results presented here have been obtained by the Unweighted Principle Component (UPC) estimation from the Stochastic Subspace Identfication (SSI) technique. The corresponding mode shapes from measurement and multibody simulation are shown in Fig. 9.

Tab. 1: Eigenfrequencies $f$ and damping ratio $z$ of the parked wind turbine - operational modal analysis techniques vs. MBS simulation

| Mode No. | Description | OMA $f$ in [Hz] | MBS $f$ in [Hz] | OMA $z$ in [%] |
|---|---|---|---|---|
| 1 | 1st Tower Mode fore-aft | 0.27 | 0.29 | 0.22 |
| 2 | 1st Edge Mode Blade - Tilting of Rotor | 0.84 | 0.88 | 0.81 |
| 3 | 1st Edge Mode Blade - Octopus | 0.97 | 0.94 | 0.80 |
| 4 | 3rd Flap Mode Blade - Eagle | 1.89 | 1.67 | 1.59 |
| 5 | 2nd Edge Mode Blade - Tower Bending | 2.62 | 2.82 | 0.93 |

As can be seen the agreement of the first tower bending mode shape in fore-aft direction is very good, see Fig. 9a. The rotor behaves almost like a rigid mass as could be expected from multibody simulation. A very interesting point is that the damping ratio $z = 0.22\,\%$ of the 3 MW wind turbine is almost equal to the value $z = 0.20\,\%$ obtained from measurements on the 2 MW wind turbine [3]. It has to be pointed out that both values lie below the structural damping ratio $z_{\mathrm{DiBt}} = 0.24\,\%$ given in the DiBt guideline [8].

The frequencies of mode 2 and 3 from Table 1 lie close to each other, too. From the corresponding mode shapes shown in Fig. 9b and c it can be noted that these both are of the same kind. While mode 2 is characterised by a tilting of the rotor in mode 3 the vibration of the rotor blades looks like the tentacles of an octopus. The damping ratios of both modes are almost equal.

Mode 4 is characterised by so-called wing beat of the upper blades, while Blade 2 pointing downwards stays almost in rest position, see Fig. 9d. Due to the extrapolation of tip displacements some differences are observed in the mode shapes of the blades. Due to restricted space inside the blade such positions have not been accessible for sensor placement. From Table 1 it can be seen that the damping ratio of this mode is much higher compared to the other ones listed there. One reason that has also been already observed from measurements on the 2 MW wind turbine [3] is the aerodynamic damping. Mode 4 differs from the other ones by a flapwise motion of the blades. Due to the larger area of attack a larger aerodynamic resistance could be expected.

In mode 5 a coupling of blade and tower bending modes is demonstrated. Compared to the measurements on the 2 MW wind turbine these modes could be identified clearly by introducing the blade measurements only. Furthermore the resolution of the measurement points in the blade is not high enough to visualise the blade mode shapes completely. Nevertheless compared to the previous measurement campaign on the 2 MW wind turbine the blade measurements represents a large step forward for the clear identification of such coupled modes.

## 5.2 Modal Analysis of the Wind Turbine Blade during different Operational States

Another important aspect designing a wind turbine is the dynamic behaviour of the blades during different operating states. Exemplary one clearly identified blade mode has been chosen for demonstration of the modal properties. The mode shape of the blade using the signal processing from Sec. 4.1 and the corresponding multibody simulation are shown in Fig. 10. In Table 2 provides the eigenfrequencies and damping ratios of the blade mode from Fig. 10

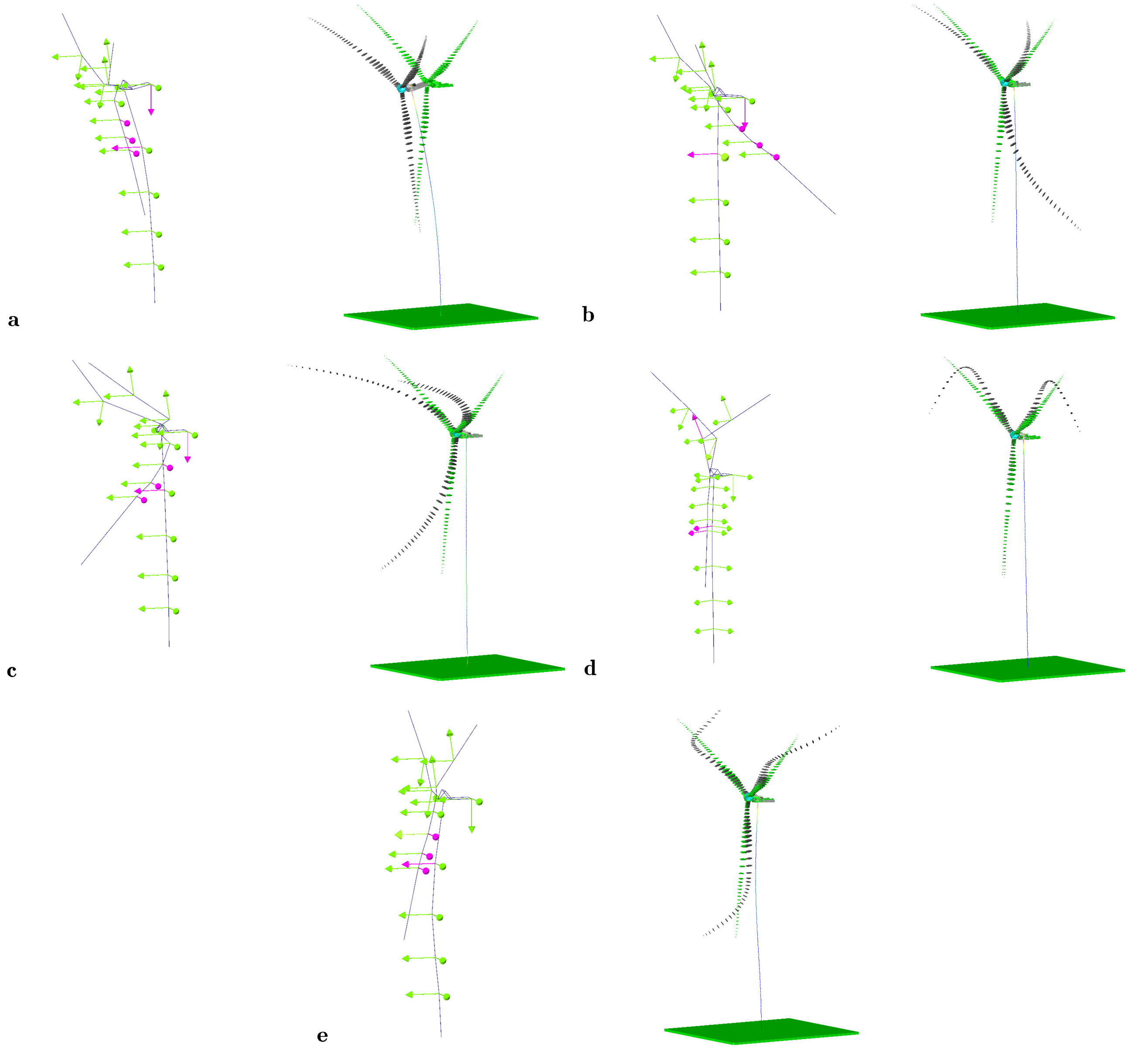


Fig. 9: Mode shapes of the parked wind turbine - Measurement (left) vs. MBS (right). **a** 1st Tower Mode fore-aft. **b** 1st Edge Mode Blade - Tilting of Rotor. **c** 1st Edge Mode Blade - Octopus. **d** 3rd Flap Mode Blade - Eagle. **e** 2nd Edge Mode Blade - Tower Bending.

for different operational states. The values are obtained using the Enhanced Frequency Domain Decomposition (EFDD) technique.

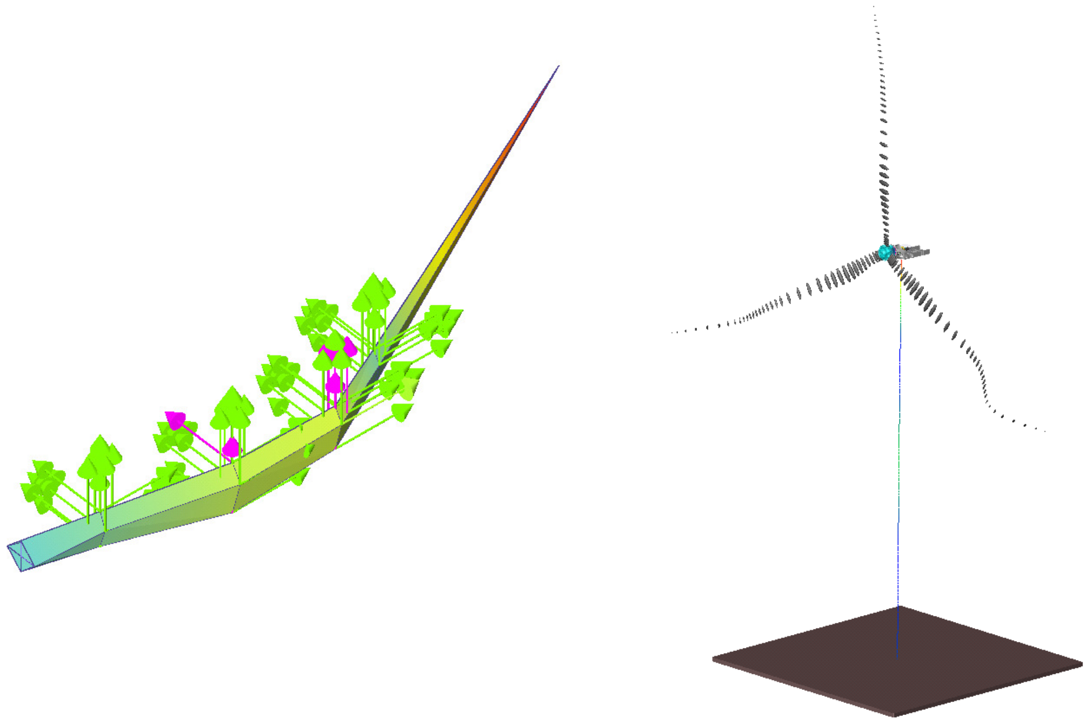

Fig. 10: Blade mode at around 4.6 Hz - Measurement (left) vs. Simulation (right)

Tab. 2: Eigenfrequencies $f$ and damping ratio $z$ of the Blade mode at around 4.6 Hz in different operational states

| | **Parked** | **Below-rated** | **Rated** |
|---|---|---|---|
| Eigenfrequency $f$ in [Hz] | 4.57 | 4.71 | 4.69 |
| Damping ratio $z$ in [%] | 1.41 | 3.17 | 4.17 |

In the parked position the rotational speed of the wind turbine is zero, while the blades are pitched to feathered position (90 deg). The rotor has not been locked so it rotates freely. Below-rated means that the wind turbine has not reached nominal power. The blades are not pitched (0 deg) during the measurement period. Rated means that the wind turbine has reached its nominal power, and the pitch angle of the blades is larger than 0 deg.

From Table 2 a trend regarding the damping ratios can be observed. While the damping ratio of the parked wind turbine is governed in large parts by the structural damping, the damping ratios for below-rated and rated operational states are mainly caused by the aerodynamic damping. It can be seen that measured damping ratios double between parked and below-rated. A further increase of about 25 % is observed between below-rated and rated operational state. Furthermore the eigenfrequency of the mode changes by 0.1 Hz between parked position and under operating conditions, while it remains almost constant between below-rated and rated operational states.

## 6 Conclusions

This contribution presents an extensive measurement campaign on a 3 MW wind turbine. The modal properties such as eigenfrequencies, mode shapes and damping ratio are estimated experimentally. The eigenfrequencies and mode shapes are compared to those obtained from a detailed multibody simulation. Good agreements have been reached, the differences in the eigenfrequencies lie below 8 %. Differences in the eigenfrequencies are seen to be related with uncertainties in the dynamical behaviour of the tower foundation. Furthermore the blades of the industrial wind turbine are prototypes which are stronger due to static blade test.

To the authors knowledge here a first application of IMUs for dynamical investigations on wind turbines is presented. A measurement and signal processing concept has been developed to combine different data acquisition systems and different sensor types. Furthermore a concept for the common evaluation of angular velocities and linear accelerations from IMUs has been evolved based on rigid body kinematics.

The results of this contribution can be used to develop a novel condition monitoring system as well as a support for model predictive control algorithms. The measured damping ratios can be used e.g. to design a overcritically excited wind turbine with less uncertainty margins with respect to its dynamic behaviour.

## Acknowledgements

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