Influence of Environmental Conditions and Damage on the Modal Properties of a Small Scale Wind Turbine –A Case Study

C.-P. Fritzen[1, a]; C. Schmidt[1, b], D. Ginsberg[1, c], I. Mueller[1, d], K. Volkmer[2, e], T. Carolus[2, f]

[1] University of Siegen, Institute of Mechanics and Control Engineering-Mechatronics
Paul-Bonatz-Strasse 9-11, 57076 Siegen, Germany
[2] University of Siegen, Institute for Fluid- and Thermodynamics
Paul-Bonatz-Strasse 9-11, 57076 Siegen, Germany
[a] claus-peter.fritzen@uni-siegen.de, [b] christoph1.schmidt@uni-siegen.de, [c] daniel.ginsberg@uni-siegen.de,
[d] inka.mueller@uni-siegen.de, [e] kevin.volkmer@uni-siegen.de, [f] thomas.carolus@uni-siegen.de

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Paul-Bonatz-Strasse 9-11, 57076 Siegen, Germany
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Abstract

In this contribution a blade of a small scale wind turbine is instrumented with an accelerometer and a strain gauge in order to measure the structural dynamic responses of the blade. Operational modal analysis (OMA) is performed by means of Stochastic Subspace Identification (SSI) methods to extract the blade eigenfrequencies out of the measured data of the operating turbine. The OMA algorithm is applied on the data over a period of several weeks at different environmental and operational conditions (EOC).

The impact of the EOCs on the modal properties is investigated. Furthermore, to analyse if the modal properties can be used as damage sensitive features for structural health monitoring of the turbine, damage is simulated by applying additional masses on the blade. The results are discussed with respect to the variations of modal properties due to changes of EOCs. The impact of damage is analysed by comparing the modal properties of all measurements directly on the one hand and by visualizing the nonlinear dependencies of the damage sensitive variables and EOCs, using Self Organizing Maps (SOM) on the other hand.

1 INTRODUCTION

Small scale wind turbines represent a segment in the wind energy branch, which is affordable also for private individuals and small to medium businesses. Using the trend towards renewables, the wind energy sector is expanding, also for small scale systems.

The University of Siegen operates a small scale horizontal axis wind turbine with 3 m rotor diameter mounted on one of their buildings. Prior usage of the turbine for power generation has shown that the blades have a high exposure to a variety of EOCs as well as loads, leading to incremental degradation of their structural integrity. This effect has already been observed for large scale wind turbines. The detailed analysis nevertheless is simplified due to easier access for this small scale wind turbine. One method to detect the degradation of the structural integrity is to analyze the modal properties. They can be used as damage sensitive features to enable structural health monitoring for wind turbine blades. However, previous studies have shown that the modal properties of civil engineering structures like television towers [1] but also large scale wind turbines [2,3] not only change due to damage but also due to varying EOCs and loads. Hence, specific knowledge about the influence of EOCs on the modal properties is necessary. Since loads and various EOCs, which affect small scale wind turbines, differ from the ones of large scale wind turbines, the observed dependencies for large scale wind turbines may not apply for small scale ones.

Therefore, this paper investigates the influence of different EOCs such as wind direction, blade temperature, and rotational speed on the modal properties of a rotor blade of a small scale wind turbine. Furthermore, the possibility in detecting damages of the blade by means of changing modal properties is investigated.

For this purpose a small scale wind turbine operated by the University of Siegen is equipped with a measurement system, including telemetric data transmission. Long-time measurements of the acceleration and strain behavior of one of the blades as well as EOC measurements are carried out. A Stochastic Subspace Identification (SSI) method is used to extract the blade eigenfrequencies and modal damping ratios out of the acceleration measurements.

The modal properties which result from the acceleration measurements are – sorted by the mode they occurred – plotted over the different EOCs to examine whether there is an impact of the EOCs. In a next step, the modal properties of the measurement without damage and the measurement with simulated damage are plotted together versus the EOCs, to see if the modal properties and the impact of the EOCs change due to damage. Furthermore, to identify damage with the help of a damage indicator, Self Organizing Maps (SOM) are used. They help to visualize underlying relations of measured variables in a simple graphical way on a two dimensional map. They are often referred to as a multi-purpose instrument for the tasks of pattern recognition and data interpretation, as they belong to the group of artificial neural networks and their map character provides additional visualization opportunities, [4]. In this paper the SOM is trained as a baseline, new data is compared to, to establish a damage indicator based on the Mahalanobis distance, as described in [5]. Alternative methods of using SOM for SHM purposes are detailed in [6,7].

2 EXPERIMENTAL INVESTIGATION

The investigations were carried out with a small scale wind turbine with a 3 m rotor diameter and a 5 m hub height which is operated by the University of Siegen and located on the roof of one of the University's buildings. The rotor blades are made of carbon-fiber-reinforced plastic (CFRP) and the blade root flange as well as the hub of aluminium, to reduce the weight of the rotor. At three points, located in 120° steps around the plant, wind direction and wind speed are measured. Furthermore the rotational speed of the shaft is recorded. A detailed description of the small scale wind turbine including informations of all electronic components and constructional conditions can be found in [8]. To measure the acceleration and strain behavior of one of the rotor blades, a piezoelectric accelerometer as well as a quarter-bridge strain gauge circuit, with the strain gauge in 45° to the blades longitudinal axis, are applied as shown in Figure 1 to the inner surface of a blade's suction side. The measurement positions are choosen according to a previous experimental modal analysis (EMA) of one of the rotor blades, conducted by the Institute of Mechanics and Control Engineering-Mechatronics, since there are no nodes expected for these positions. Measurements of the blade temperature are taken at the same position as the strain measurements using a Pt100 temperature sensor. To record the data from the blade sensors during operating condition of the plant, a telemetric system was installed to the rotor and the nacelle (see Figure 2). Figure 2 a) shows the system under operating condition and

Figure 2 b) the electronics before the assembly. A device to carry the moduls of the telemetric system (Figure 2 (6)) is mounted frontal to the hub (Figure 2 (4)) and covered by a hood (Figure 2 (5)) to protect the electronics.

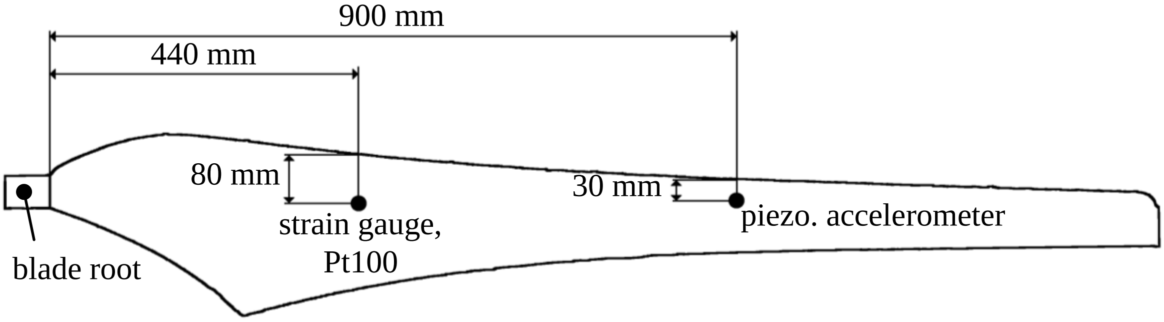

Figure 1: Draft of the instrumented rotor blade.

The eight moduls from Kraus Messtechnik GmbH (KMT) are attached on the outer diameter of the device. In particular, these are three acquisition modules, for the three sensors, one encoder module, one transmitter module and one module for inductive power supply. The data and power transfer occurs between two coils which are embedded in a disc (Figure 2 (3)) and two inductive transfer heads from KMT. These are: an inductive power-head (Figure 2 (1)) which is connected to a power supply (Figure 2 (7)) and an inductive pick-up head (Figure 2 (2)) which is connected to a decoder (Figure 2 (8)). The power supply and the decoder are located at the bottom of the tower and the power and data lines are placed inside the tower. Furthermore, the decoder is connected to a data acquisition card, which is installed into a measurement computer.

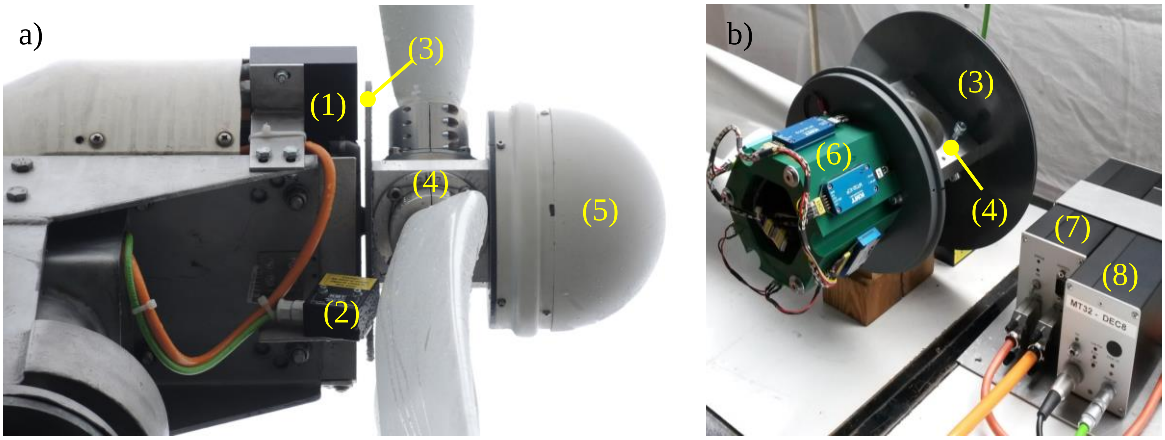

Figure 2: Telemetric data transmission system. inductive power-head (1), inductive pick-up head (2), coil disc (3), hub (4), hood (5), modul device with telemetric modules (6), power supply (7), decoder (8)

The signals are sampled with 12,5 kHz, filtered with an 8th-order low-pass Butterworth filter with a cut-off frequency of 650 Hz, downsampled to 2,5 kHz, whereas the temperature signal is downsampled to 10 Hz, and saved to the measurement computer. To fulfill the white noise excitation requirement of OMA as good as possible, the amount of data is reduced to the data whose fluctuations of the excitations are smaller than a choosen level. Therefore the signals are cut into 60 s long intervalls and only the intervalls with a nearly constant behavior of the rotational speed n are considered, since the wind speed, which influences the rotational speed due to the tip-speed ratio, is the excitation which fluctuates the most. In the range of 0–50 1/min only intervalls with a standard deviation below 10 1/min and in the range of 50–450 1/min only intervalls with a standard deviation below 20 1/min are considered. No overlapping intervalls or intervalls with a standstill of the rotor where choosen. Thus, 225 intervalls were determined for the measurements of the undamaged condition in the period of 12. Sept. 2015–24. Sept. 2015 and 156 intervalls for the measurements with simulated damaged in the period of 06. Nov. 2015–09. Nov. 2015.

Since a change of the system properties of a linear multi degree of freedom system could be attributed to a change of the mass and stiffness matrices [9], the simulation of damage was performed by adding masses of 100 g selective onto the pressure side of each of the 1100 g heavy rotor blades in a distance of half of the blade length away from the tip.

3 USED METHODS

To investigate the impact of the EOCs and damage to the changes of the modal properties, the distributions of the single measurements are considered. In this paper an approach using a SOM for distinguishing changes of EOCs and damage is presented. The SSI method, which is used to calculate the modal properties, will be introduced shortly. Afterwards a brief explanation of the theory of SOM is given.

3.1 SSI BASED CALCULATION OF MODAL PROPERTIES

The Stochastic Subspace Identification method (SSI) is an output-only system identification method to identify a state space representation of the equation of motion of a linear system. With the state space vector $\boldsymbol{z}_k$, consisting of the displacement and velocity vector and the output vector $\boldsymbol{y}_k$ at the discrete time points k, the state and the output equation for a discrete time system under stochastic excitation are as follows:

$$\begin{aligned} \boldsymbol{z}_{k+1} &= \boldsymbol{A}_d \boldsymbol{z}_k + \boldsymbol{w}_k \\ \boldsymbol{y}_k &= \boldsymbol{C}_y \boldsymbol{z}_k + \boldsymbol{v}_k \end{aligned} \tag{1}$$

With the discrete time (index d) system matrix $\boldsymbol{A}_d$ and the output matrix $\boldsymbol{C}_y$. Vector $\boldsymbol{w}_k$ represents the excitation signal and $\boldsymbol{v}_k$ the measurement noise. Both vectors are unmeasurable noise processes, which can be described by uncorrelated, stationary white noise with zero mean [9,10]. Solving the following eigenvalue problem,

$$(\boldsymbol{A}_d - \delta_i \boldsymbol{I})\boldsymbol{\psi}_i = 0 \tag{2}$$

and transforming the complex time diskrete eigenvalues δ_i, to the continuous time eigenvalues λ_i, leads to the eigenfrequencies f_i, modal damping ratios ξ_i and mode shapes $\boldsymbol{\varphi}_m$ of a system with m degrees of freedom:

$$\begin{aligned} f_i &= \frac{\mathrm{Im}(\lambda_i)}{2\pi} \\ \xi_i &= -\frac{\mathrm{Re}(\lambda_i)}{|\lambda_i|} \end{aligned} \tag{3}$$

$$\boldsymbol{\Phi} = [\boldsymbol{\varphi}_1 \, \boldsymbol{\varphi}_2 \, \ldots \, \boldsymbol{\varphi}_m] = \boldsymbol{C}_y \boldsymbol{\Psi}$$

To solve the eigenvalue problem (Eq. 2) and calculate the modal parameters (Eq. 3), estimates for the unknown system and output matrix are needed. The idea of the SSI method is to obtain the estimation of the state space representation by performing a singular value decomposition of a Hankel matrix $\boldsymbol{H}$, which consists of estimations of output covariance matrices of the measured time data [9]. Further informations about the SSI method can be found in [11]. To distinguish between physical (stable) and mathematical (unstable) poles stabilization diagrams of the measurements, which are estimated from the SSI method, are used. Poles which fullfil defined stabilization criteria – as described in [9] – are considered to be physical poles and therefore highlighted in the diagram. To simplify the selection of the stable poles, the power spectral density curves of the measurement intervalls are plotted inside the stabilization diagrams as well (Figure 3). Moreover, no poles were selected which correspond to a harmonic of the angular frequency of the rotor.

3.2 USE OF SOM TO BUILD A DAMAGE INDICATOR

With the help of a SOM it is possible to model nonlinear dependencies of damage sensitive variables and EOCs. A two-dimensional map is related to a q-dimensional feature space, which includes the damage sensitive variables and the EOCs in a vector $\boldsymbol{x}$. Based on this two-dimensional display, which consists of different units, new data is compared to the map by calculating the Mahalanobis squared distance. Three steps are necessary to use SOM for damage identification under changing EOC: training of the map, comparison using the Mahalanobis distance and decision. For the training step, data of the undamaged structure at different EOCs is used. It enables the calculation of the baseline as a SOM. In the second step new data $\boldsymbol{x}$ is projected on the SOM. The unit which matches best to the data is used as reference point with the vector $\boldsymbol{m}_c$ in the q-dimensional feature space. The Mahalanobis distance between $\boldsymbol{x}$ and $\boldsymbol{m}_c$ is calculated and used as damage indicator DI. For this the covariance matrix $\boldsymbol{V}$ for the reference distances from the training data has to be known.

$$DI = (\boldsymbol{x} - \boldsymbol{m}_c)^T \boldsymbol{V}^{-1} (\boldsymbol{x} - \boldsymbol{m}_c) \tag{4}$$

If the damage indicator DI is significantly larger than the DI for data of the undamaged state, the new data belongs to a damaged state. This is identified in the decision step. The method is explained in detail in [5].

4 RESULTS

To select the stable poles and construct the stabilization diagram, following tolerance values for stable frequencies and stable damping ratios are used:

$$ftol = 0{,}05\ \%, \qquad dtol = 5\ \%$$

With only one acceleration sensor and one strain gauge, it was not possible to identify mode shapes, hence the mode shapes and thus the third criterion are not considered in this investigation. The model order of the used algorithm is between 4 and 80. Five different modes in a range from 20 Hz to 235 Hz have been determined, although not every mode was excited for each interval as it can be seen in Figure 3.

Comparison of the measurements have shown, that the acceleration measurements are better than the strain measurements to identify the modal parameters since the strain signal has a bad signal to noise ratio for higher frequencies. Hence the following investigations are carried out using the acceleration measurements.

Figure 4 shows the identified eigenfrequencies of the modes versus the mean values of the blade temperature, wind direction and rotational speed. In addition to that, best fit lines using robust regression, created with the MATLAB function *robustfit*, are plotted into the diagrams in order to visualize potential impacts of the EOCs on the modal properties. The results of the modal damping ratios are not presented, since it is well known, that the modal damping ratio is estimated with less accuracy in OMA. Therefore, it is not possible to analyze the impact of the EOCs on the modal damping ratio by means of the results of this study. According to the previous EMA, the modal damping ratios of the investigated rotor blade should be between 0,3 % and 0,9 %.

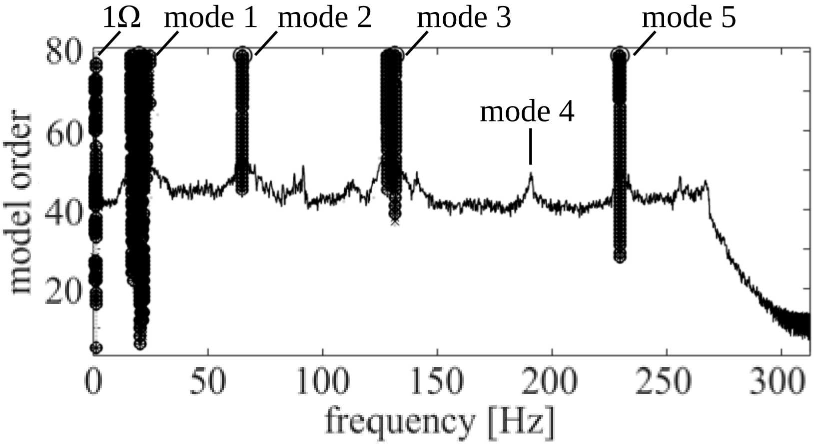

Figure 3: Stabilization diagram of a 60 s interval of the acceleration measurement with n = 55,58 1/min, T_{blade} = 13,6 °C, wind direction = 87 °. Mode 1, 2, 3, 5 excited.

Looking at the changes of the eigenfrequencies regarding to the blade temperature, no uniform behavior can be observed. The eigenfrequencies of mode two, three and five decrease with increasing temperature, whereas the eigenfrequencies of mode one and four increase. Since the changes of the eigenfrequencies are very low, no obvious impact of the blade temperature to the eigenfrequencies can be identified. The changes of the eigenfrequencies regarding to the wind direction are all showing the same trend, except for the fourth mode whose best fit line is questionable at any rate, since there are only very few stable poles. The values of the eigenfrequencies are higher for wind flows from Northwest (270°) than from East-southeast (112,5°) and increase in clockwise direction. During the measurement time, no wind flow from other directions occurred. Hence, an impact of the wind direction on the eigenfrequencies can be observed. This impact may result from varying structural and constructive properties of the plant with regard to the direction. Moreover, in between 200° and 270° the highest values for the wind speed up to 10 m/s has been observed. Focussing on this region in detail, mode one, four and five seem to have a strong separate distribution of data points for high wind speed values. Looking at the eigenfrequencies versus the rotational speed, the first three modes seem to be excited more often for lower revolutions, whereas the fourth and fifth mode occurred for high rotational speed values. This coincides with the observed dependence of modes four and five to high wind speed values. Also the dependence of high wind speed or high rotational speed on the separate distribution of data points of mode one can be confirmed. Apart from mode four which, as mentioned before, has only a little few amount of stable poles, the eigenfrequencies of all modes increase with increasing rotational speed, with a maximum of 0,028 Hz/min^{-1} for mode three. This increase may be caused by the rise of the longitudinal stiffness of the rotor blades for increasing rotational speed.

To analyse the influence of damage to the eigenfrequencies of the structure and to the previously observed impact of the EOCs, Figure 5 shows the data points of the measurements without damage and the measurements with simulated damage versus the EOCs.

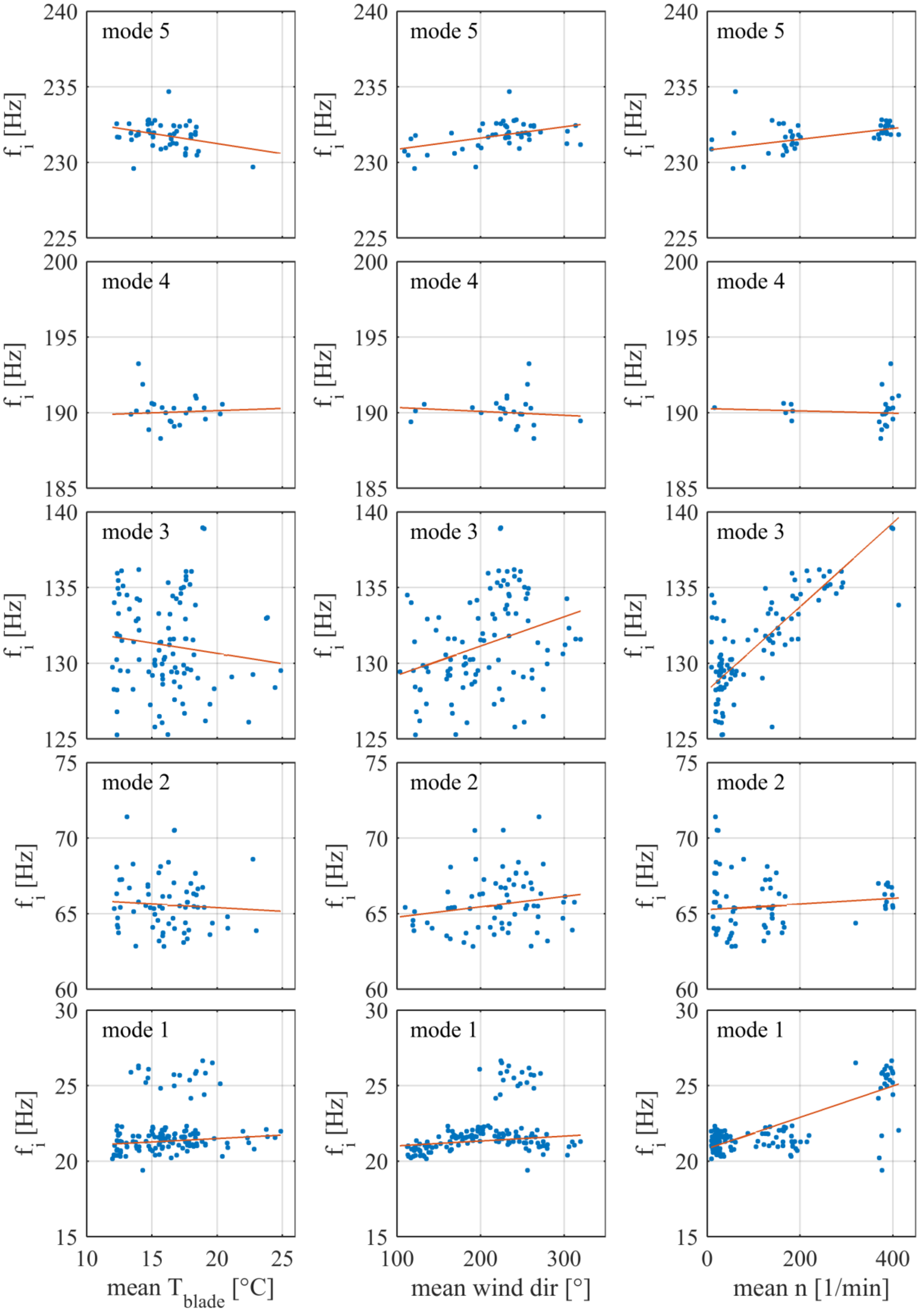

Figure 4: Eigenfrequencies of the five occurred modes versus mean blade temperature, mean wind direction and mean rotational speed including best fit lines.

The eigenfrequencies of the first and the third mode did not change and the impact of the EOCs stayed the same for all five modes. However, a slight decrease of the eigenfrequency of mode two and a strong decrease of the eigenfrequency of mode four and five could be observed. Since all data points of the measurements with damage of mode four and five, apart from one outlier, are outside the scatter band of the undamaged measurements, the change of the eigenfrequencies is propably caused by the simulated damage.

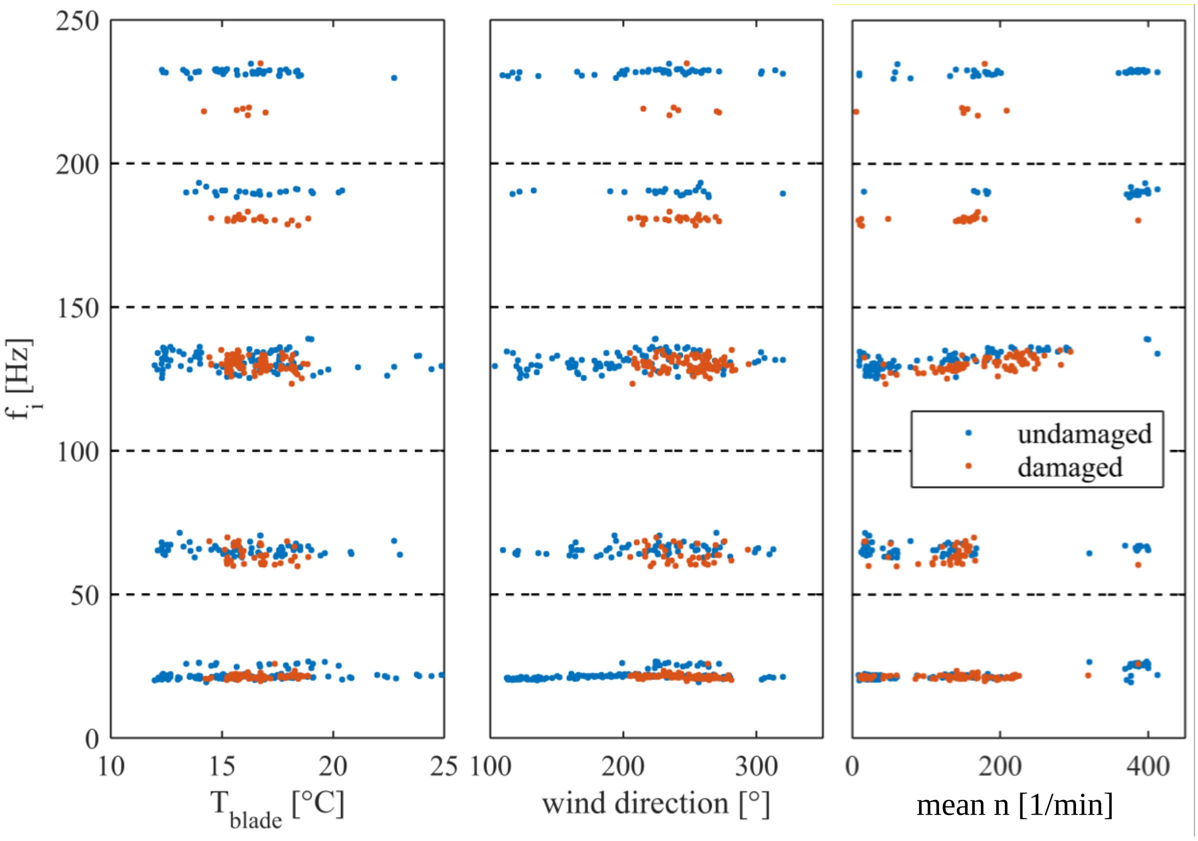

Figure 5: Eigenfrequencies undamaged (blue) and damaged (red) of the five occurred modes versus mean blade temperature, mean wind direction and mean rotational speed.

The use of features like the eigenfrequency and its change due to structural damages for the identification of damages is possible and a well-known procedure for vibration-based SHM. Nevertheless the influence of environmental and operational conditions might mask the changes, caused by structural damages. Based on these results, the procedure of training a SOM to cope with changing EOC will be shown here, using the theory described in section 3 and in [5]. As feature vector $\boldsymbol{x}$ the EOCs (temperature, wind direction and rotor speed), as well as the damage sensitive features (Eigenfrequencies over 150 Hz) have been chosen. For the gathered data in this case study, the change of the temperature is comparably small. Nevertheless, the procedure to use SOM is used to achieve a damage index. Based on the feature vector, the SOM is calculated, using two thirds of the baseline data as training data. The other third of the baseline data, is used to test the method. For this partitioning it has to be secured that the used EOC conditions of the test data still represents the whole range of EOCs. Moreover, only those data can be used, which exhibits the eigenfrequencies over 150 Hz. This reduces the number of data points for this procedure. For this test data of the undamaged state and test data, measured in the state with modeled structural damage, the

Mahalanobis squared distance is calculated and used as damage indicator *DI*. Additionally *DI* is calculated for the training data. This data can be used as reference. The results are shown in Figure 6. While the test data exhibits *DI*s, which are in a similar range like the training data, the *DI*s for all data points, based on data of the damaged state, have been increased.
Using this method, it is possible to distinguish between EOC and damage in an automated way, also for larger ranges of EOC, as they occur for measurements over a longer period of time.

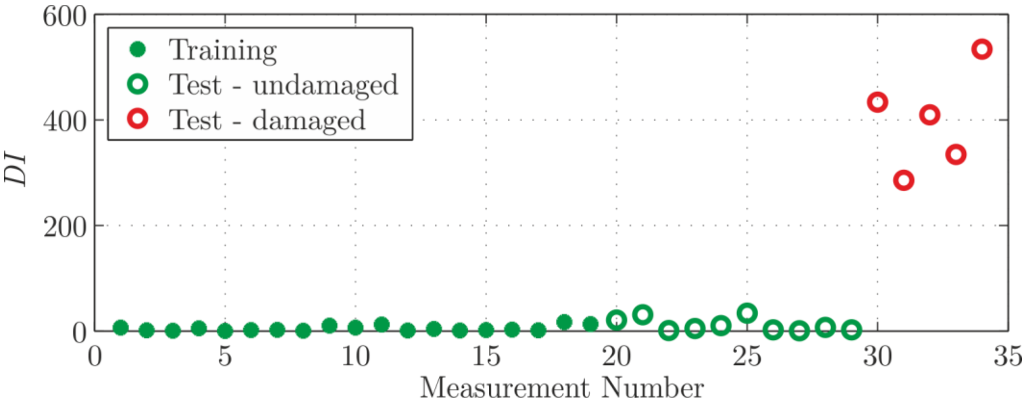

Figure 6: Damage indicator DI of the training data, the undamaged test data as well as the damaged test data.

9 CONCLUSIONS

A small scale wind turbine has been instrumented with an acceleration sensor, a strain gauge and a temperature sensor as well as a telemetric data transmission system to measure the system characteristics of one of the turbines rotor blades during operating condition. Operational modal analysis of the acceleration measuremets have been used to investigate whether it is possible to achieve qualitative results using only one sensor. To fullfil the requirement of OMA the measurements were cut into 60 s long intervalls to assume the system to be time-invariant even if it is in fact time-variant. To investigate the influence of environmental and operational conditions and damage to the modal properties of the blade, measurements of the wind direction, blade temperature and rotational speed as well as measurements with simulated damage were carried out.

The influence of the blade temperature, wind direction and rotational speed to the modal properties of a small scale wind turbine have been presented. Furthermore, the changes of the modal properties due to damage of the instrumented rotor blade have been discussed. With only one acceleration sensor, no mode shapes have been identified. The modal damping ratio has not been discussed in this investigation. An impact of the wind direction and rotational speed to the eigenfrequency could have been identified. The damage of the rotor blade was detected through changes of the eigenfrequencies of mode four and five. For a better distinction between the impact of EOCs and damage to the modal properties of the rotor blade a damage indicator *DI* was calculated using the SOM method. It has been shown that the SOM is very suitable in detecting a damage of the rotor blade even for larger ranges of EOCs.

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REFERENCES

[1] Carne, T. G., & James, G. H. (2010). The Inception of OMA in the Development of Modal Testing Technology for Wind Turbines. *Mechanical Systems and Signal Processing , 24* (5), 1213-1226.

[2] Kraemer, P., & Fritzen, C.-P. (2010). Aspects of Operational Modal Analysis for Structures of Offshore Wind Energy Plants. *28th International Modal Analysis Conference (IMAC) A Conference & Exposition on Structural Dynamics* (145-152). Jacksonville: Society for Experimental Mechanics.

[3] Niu, Y., Kraemer, P., & Fritzen, C.-P. (2012). Operational modal analysis for the Canton Tower. *Smart Structures & Systems , 10* (4), 393-410.

[4] Kohonen T. Self-organizing maps. Berlin: Springer, 2001.

[5] Buethe I, Kraemer P and Fritzen C-P. Applications of self-organizing maps in structural health monitoring. KeyEng Mat 2012; 518: 37–46.

[6] Torres-Arredondo, M. A.; Tibaduiza, D. A.; Buethe, I.; Mujica, L. E.; Vejar, M.; Rodellar, J. & Fritzen, C.-P. Khosrow-Pour, M. (Ed.) Methodologies of Damage Identification using Non-linear Data-Driven Modelling IGI Encyclopedia of Information Science and Technology, 2014

[7] Mujica, L. E.; Vehi, J. & Rodellar, J. Non-destructive testing for assessing structures by using soft-computing Artificial Neural Networks - Icann 2006, Pt 2, Springer-verlag Berlin, 2006, 4132, 982-991

[8] Volkmer, K., & Adam, T. (2016). The wind turbine of the University of Siegen. University of Siegen, Institute of Fluid- and Thermodynamics, Siegen.

[9] Kraemer, P. (2011). *Schadensdiagnoseverfahren für die Zustandsüberwachung von Offshore-Windenergieanlagen.* Dissertation, University of Siegen, Institute of Mechanics and Control Engineering-Mechatronics, Siegen.

[10] Balageas, D., Fritzen, C.-P., & Güemes, A. (2006). Structural Health Monitoring (1. Ed.). London: ISTE Ltd.

[11] Brincker, R., & Andersen, P. (2006). Understanding Stochastic Subspace Identification. *24th International Modal Analysis Conference (IMAC) A Conference & Exposition on Structural Dynamics.* St. Louis: Society for Experimental Mechanics.