Assessment of Mode Shape-Based Damage Detection Methods under Real Operational Conditions

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ABSTRACT

The application of vibration-based damage detection methods to a wind turbine model is analyzed in this paper. The target is to develop a system that detects and locates damage on a structure subjected to wind excitation. With the proposed procedure vibration data is first processed by an Operational Modal Analysis. The extracted mode shapes are subsequently evaluated by two damage detection algorithms: the Modal Strain Energy method and the Gapped Smoothing Technique. Different types of damage are investigated, including tower damage and a change of foundation stiffness. First, a numerical prestudy is conducted to give information about suitable measurement quantities and density of measurement positions on the structure. Based on the numerical results an experimental setup is arranged, including the equipment of the tower with strain gauges and accelerometers. The results of the experimental work show that locating damage with the proposed approach is feasible.

INTRODUCTION

Structural health monitoring methods are of increasing interest for the monitoring of large infrastructure objects like buildings, bridges or wind turbines. An important topic of research concerns the transfer of SHM methods to practical applications [1]. A wide range of damage sensitive features has been investigated [2]. Two promising methods within the mode shape-based SHM are the Modal Strain Energy method (MSE) [3] and the Gapped Smoothing Technique (GST) [4]. Both methods are reported to have predominantly been investigated on beam or plate type laboratory structures [5]. One exception however is the application of the MSE to mode shapes of a real bridge [6].

In order to apply the methods to real world structures excited by ambient vibration, it is necessary to extract mode shapes during operation. A small amount of communication is desirable for monitoring systems consisting of a high number of sensors distributed widespread over the structure [7]. An appropriate approach is the combination of the Random Decrement (RD) technique and Operational Modal Analysis (OMA) [8, 9]. It offers the possibility to acquire RD data on separate sensor nodes with a given number of averages. Subsequently the collected information is asynchronously sent to a central analysis unit, i.e. without demand for real time communication. On the central processing unit, a set of mode shapes is calculated while the data acquisition within the sensor nodes starts anew.

APPROACH FOR STRUCTURE MONITORING

A decentralized signal processing system developed at Fraunhofer LBF is used for a Random Decrement based estimation of correlation functions. The spectral density matrix $\boldsymbol{G}(f)$, resulting from the correlation matrix is subjected to a Singular Value Decomposition

$$\boldsymbol{G}(f) = \boldsymbol{U}(f)\boldsymbol{S}(f)\boldsymbol{U}^H(f) \qquad \text{(Eq.1)}$$

which leads to fully populated matrices $\boldsymbol{U}(f)$ and a diagonal matrix $\boldsymbol{S}(f)$ holding the spectra of the singular values (SV). The peak values of the first singular values are interpreted as indicators for the system's eigenfrequencies. The estimated mode shapes are found as the first column of $\boldsymbol{U}(f)$ according the eigenfrequencies. A detailed description of the procedure can be found in [7].

The damage detection algorithms in this paper are originally based on mode shape curvatures, which have been found to be a sensitive feature for localizing damage in a structure [10]. Due to the proportionality of surface strains and curvatures, curvatures can directly be measured by applying strain sensors to a structure [4]. However, mode shapes ϕ acquired by e.g. accelerometers need to be post-processed by a 2nd order central difference approximation in order to receive the mode shape curvature ϕ''.

Assuming the stiffness of the structure to be constant, the fraction of **Modal Strain Energy** stored in a sub-region of the beam around node i to that stored in the entire beam can be expressed as [6]

$$F_{ij}^{ref} = \frac{\left(\phi_{ij}^{ref''}\right)^2}{\sum_1^{i_{max}}\left(\phi_{ij}^{ref''}\right)^2} \qquad \text{(Eq. 2)} \qquad\qquad F_{ij}^{d} = \frac{\left(\phi_{ij}^{d''}\right)^2}{\sum_1^{i_{max}}\left(\phi_{ij}^{d''}\right)^2}, \qquad \text{(Eq.3)}$$

where i_{max} is the total number of nodes, j is the number of the mode shape and indices ref and d denote the reference and the damaged states of the structure, respectively. A damage index (DI) that evaluates the changes of the MSE is given by Eq.4 [3]. It will be shown in this paper, that the DI derived from Eq.4 is sensitive to damage. However, it yields maxima or minima at the damage location, depending on the evaluated mode shape. The following convention is used in order to achieve maxima at the damage location for the first bending mode shape: curvatures (index $curv$) are evaluated using the original damage index function (Eq. 4), deflection or acceleration mode shapes (index ms) are evaluated using its inverse (Eq. 5).

$$DI_{ij}^{curv} = \frac{F_{ij}^{d} + 1}{F_{ij}^{ref} + 1} \qquad \text{(Eq. 4)} \qquad\qquad DI_{ij}^{ms} = \frac{F_{ij}^{ref} + 1}{F_{ij}^{d} + 1} \qquad \text{(Eq.5)}$$

If a total of $n = 1 \ldots N$ measurements of the reference structure are disposable, Eq.2 is built using $\overline{\phi_{ij}^{ref''}}$, which is the mean of $\phi_{ijn}^{ref''}$ across all measurements N. For each of the $m = 1 \ldots M$ measurements of the damaged structure a DI is calculated using Eq.4

or Eq.5, respectively, and normalized according to Eq. 6, where μ is the mean and σ is the standard deviation of the DI_{jm} across the nodes i. The DI including all measurements is then calculated according to Eq.7.

$$DI_{ijm}^{n} = \frac{DI_{ijm} - \mu(DI_{jm})}{\sigma(DI_{jm})} \qquad \text{(Eq.6)} \qquad\qquad DI_{ij} = \frac{1}{M}\sum_{m=1}^{M} DI_{ijm}^{n} \qquad \text{(Eq.7)}$$

The **Gapped Smoothing Technique** (GST) is based on the difference between a mode shape curvature ϕ'' and a cubic polynomial C_i. A separate polynomial is calculated for each node i on the structure. For a beam-type structure a cubic polynomial can be calculated according to:

$$C_i = a_0 + a_1 z_i + a_2 z_i^2 + a_3 z_i^3, \qquad \text{(Eq. 8)}$$

where z_i is the coordinate of node i. The coefficients a_0, a_1, a_2, and a_3 of the polynomial C_i are determined using only the data of the neighboring nodes ϕ''_{i-2}, ϕ''_{i-1}, ϕ''_{i+1} and ϕ''_{i+2}, but ignoring the data of the node i. Peaks within the curvature, eventually caused by damage, cannot be followed by the polynomial. Hence, the irregularity function for each mode shape j

$$\delta_{ij} = C_{ij} - \phi''_{ij} \qquad \text{(Eq. 9)}$$

will have a maximum, which corresponds to this peak. Accordingly for this paper the GST-based damage index is formulated as

$$DI_{ij} = \frac{\left|\delta_{ij}^{d} - \delta_{ij}^{ref}\right|}{\left|\delta_{ij}^{ref}\right|}. \qquad \text{(Eq. 10)}$$

For a total of N measurements of the reference, the reference input δ_{ij}^{ref} of Eq.10 will be replaced by its mean $\overline{\delta_{ij}^{ref}}$ across all measurements N. One DI_{ijm} will then be calculated for each measurement of the damaged structure. The normalized damage index and DI including all measurements is calculated using Eq.6 and Eq.7.

INVESTIGATED STRUCTURE

The structure used as a test object for this feasibility study is a small model of a wind turbine (rotor diameter approx. 0.5 m). The nacelle (0.5 kg) is mounted on an aluminium beam with a total length of 1350 mm. The structure is investigated under different wind conditions. Therefore measurements have been conducted in-the-field , Figure 1a), where the turbine is placed on the roof of our institute where it is exposed to real wind loads. In the laboratory the structure is excited by a constant wind field, Figure 1b), generated by a fan placed 1m behind the model. Dimensions and the position of the lowest and the upmost sensor are illustrated in Figure 1c).

Two artificial and reproducible damages are designed: a loss of the foundation stiffness is simulated by assembling and disassembling a bar of the pedestal, Figure 2a) and b). Further, a steel collar (400g) can be attached to or removed from the tower in a high (850 mm) and a low position (440 mm from ground) that locally changes tower stiffness and mass properties, Figure 2 c). In the following the damage types are also referred to as *high pos*, *low pos* and *found*. Concerning the application of the damage detection algorithms needs to be stated that *reference* input data is yield by the stiffer structure. E.g. the collar attached to the structure stiffens the structure, thus its vibration data yields the reference input.

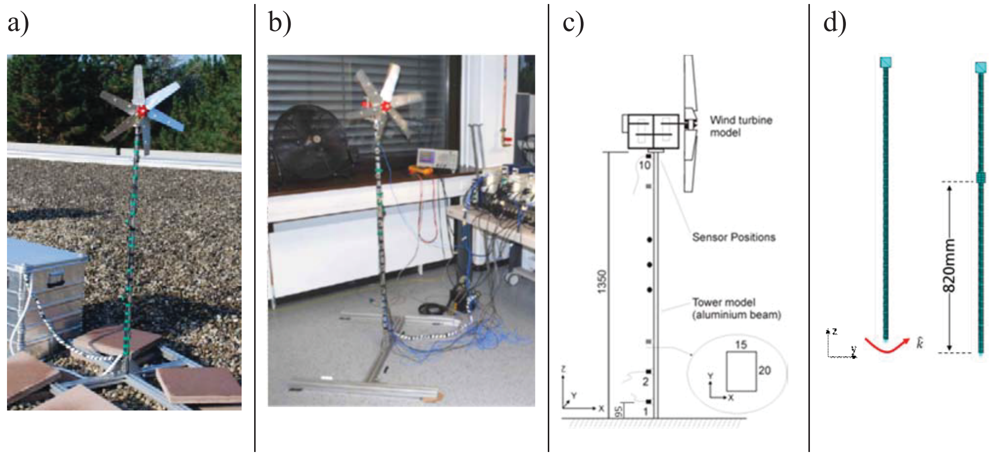

Figure 1: Test structure a) in the field, b) in the laboratory, c) sensor positions and dimensions [mm], d) FE model of the test structure

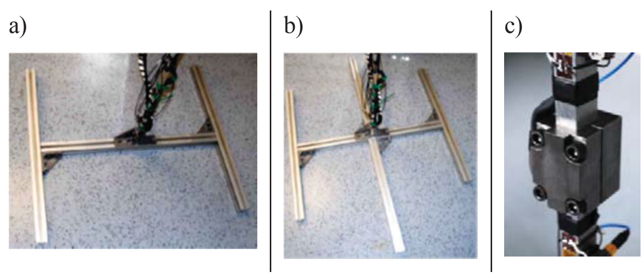

Figure 2: a) flexible foundation, b) stiff foundation, c) collar

NUMERICAL PRESTUDY

A numerical prestudy is conducted to provide information about the number and the type of sensors required for detecting the defined damages. A simple finite element model, Figure 1d), of the structure has been generated with Ansys. Strain and deflection mode shapes are extracted from the numerical model using 5, 10 and 20 equidistantly distributed nodes along the tower. The position of the lowest and the upmost node accord to the indication given in Figure 1c).

Figure 3 illustrates the localization procedure using GST. Figure 3a) and b) show the curvatures and their according polynomial for 2nd acceleration mode shape of a reference and a damaged structure. The DI diagram, Figure 3c), illustrates the sensitivity of the GST for the damage induced deviations between curvature and its polynomial, while the interpolation inaccuracies close to the boundaries stay without impact.

However, analyzing the accuracy of the curvatures calculated from deflection mode shape reveals a high sensitivity to slightly polluted data. Figure 4a) shows the 1st deflection mode shape of a reference structure and the same shape polluted with 1% of noise. Although the mode shapes hardly show any deviation, the derived curvatures deviate significantly. This characteristic suggests curvatures derived via central difference approximation to be unsuitable for damage detection.

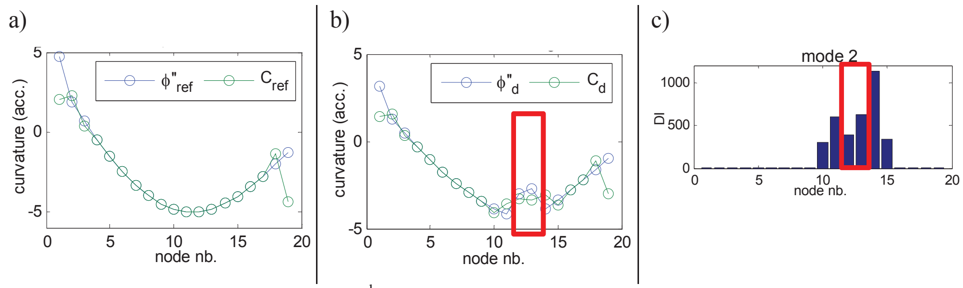

Figure 3: GST applied to the 2nd deflection mode shape of the numerical model, unmodified structure (left), collar attached between node 13 and 14 (middle), resulting DI-diagram (right)

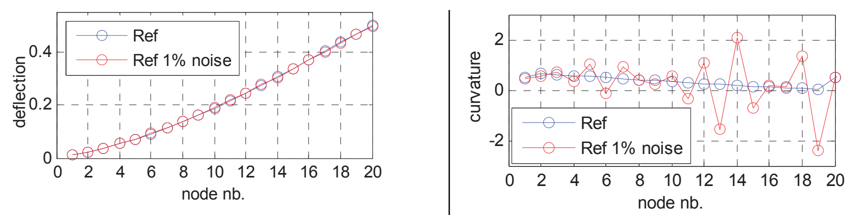

Figure 4: Influence of noise to the curvatures derived from deflection mode shapes

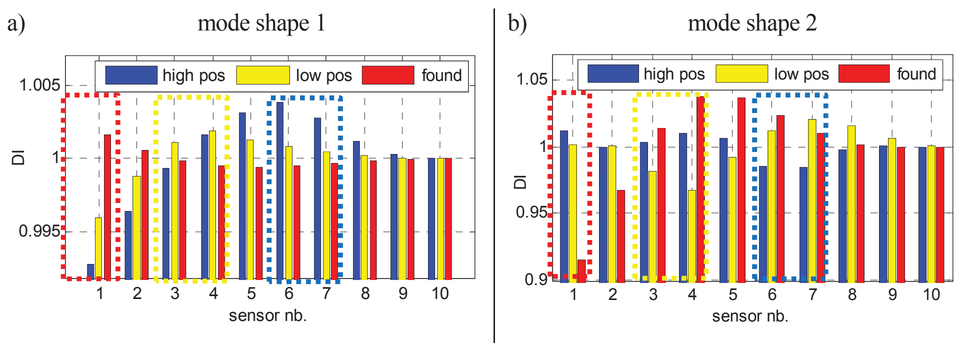

Figure 5: DI diagrams for MSE derived from strain data for different damage types, dashed boxes indicate nodes adjacent to the damage location

Table 1: Sensitivity of the damage detection algorithms (max=global maximum, min = global minimum, (max) = significant local maximum in the DI diagram at damage location)

Damage type	Nb. nodes	Strain curvatures				Deflection curvatures				Deflection mode shapes			
		MSE		GST		MSE		GST		MSE		GST	
		MS1	MS2	MS1	MS2	MS1	MS2	MS1	MS2	MS1	MS2	MS1	MS2
High position	5	**max**	**min**	-	-	**max**	**min**	-	-	**max**	**min**	-	-
	10	**max**	**min**	**max**	**max**	**max**	-	**max**	**max**	**max**	-	-	**max**
	20	**max**	**min**	**max**	**max**	**max**	**max**	**max**	**max**	**max**	-	**max**	**max**
Low position	5	**max**	**min**	**max**	**max**	**max**	**min**	-	-	**max**	-	-	-
	10	**max**	**min**	**max**	**max**	**max**	-	**max**	**max**	**max**	-	-	-
	20	**max**	**min**	**max**	**max**	**max**	-	**(max)**	**(max)**	**max**	**max**	**max**	**max**
Foundation	5	**max**	**min**	-	-	**max**	-	**max**	-	-	-	**max**	-
	10	**max**	**min**	-	-	**max**	-	**max**	-	-	-	**max**	-
	20	**max**	**min**	-	-	**max**	-	-	-	-	-	**max**	-

Table 1 summarizes the sensitivity of the damage detection algorithms in relation to the damage type, mode shape (MS) number, the number of nodes and the physical quantity type. It turns out that evaluating strain curvatures using MSE method yields a high sensitivity to all kind of damage. Using GST tower damage can be located if at least 10 nodes are disposable. High sensitivity to damage can also be attested to deflection curvatures, when the 1st mode shape curvature is evaluated using MSE and if the GST is used with at least 10 nodes. However, even the 1st deflection mode shapes yield correct damage locations when fed into the MSE algorithm.

EXPERIMENTAL EVALUATION

Based on the results of the numerical prestudy the test structure is equipped with 10 Brüel&Kjaer accelerometers (100 mV/g) and 10 strain measurement positions (2 HBM strain gauges are arranged in a bridge circuit at each location) measuring motion in y-direction. The number of 10 sensor positions is chosen because it is an appropriate compromise between hardware requirements and the ability to locate damage.

A preceding experimental modal analysis (EMA) measured the modal frequencies of mode shapes in y-direction at 4.2Hz and 33Hz. However, due to gyroscopic effects significant motion in y-direction appears at 26.6Hz, which actually corresponds to the 2nd bending mode shape in x-direction.

This characteristic also appears in the SV diagram derived from the acceleration measurements, Figure 6. A significant peak is related to the first bending mode at 4.2Hz. However, here the peak at 26Hz is more dominant than the peak at 33Hz, which is a common pattern to the SV diagrams of acceleration measurements within this work. The SV diagram derived from strain data also reveals a significant peak at 4.2Hz, a peak at the frequency of the 2nd bending mode, however, is hardly existent and thus this mode is not observable with the implemented system.

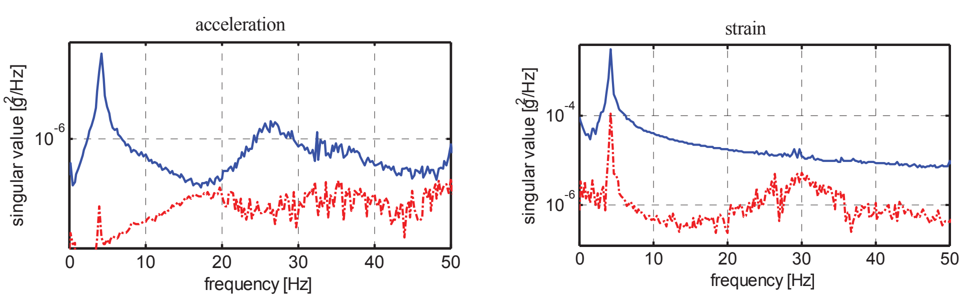

Figure 6: SV diagrams from the field measurements acceleration data strain data

The extracted mode shapes reflect this behaviour. Figure 7 exemplarily shows mode shapes extracted from in-the-field and laboratory measurements. It can be deduced, that the 1st mode shapes are reproducible for acceleration and strain data. However, the estimated 2nd acceleration mode shape scatters. The comparison also illustrates high repeatability of the mode shapes, independent of the character of the wind excitation.

Due to the reduced accuracy of the estimated 2nd mode shapes, the damage detection analysis is concentrated on the 1st mode shapes of strain and acceleration measurements, Figure 8. The laboratory measurements are used for evaluation, since the number of acquired measurements (nb.meas.) in laboratory is larger than that acquired in the field. It can be deduced from the diagrams that the MSE algorithm is sensitive to damage location. As predicted by the numerical prestudy, the collar attached to the tower results in maxima within the DI diagrams for both, strain and

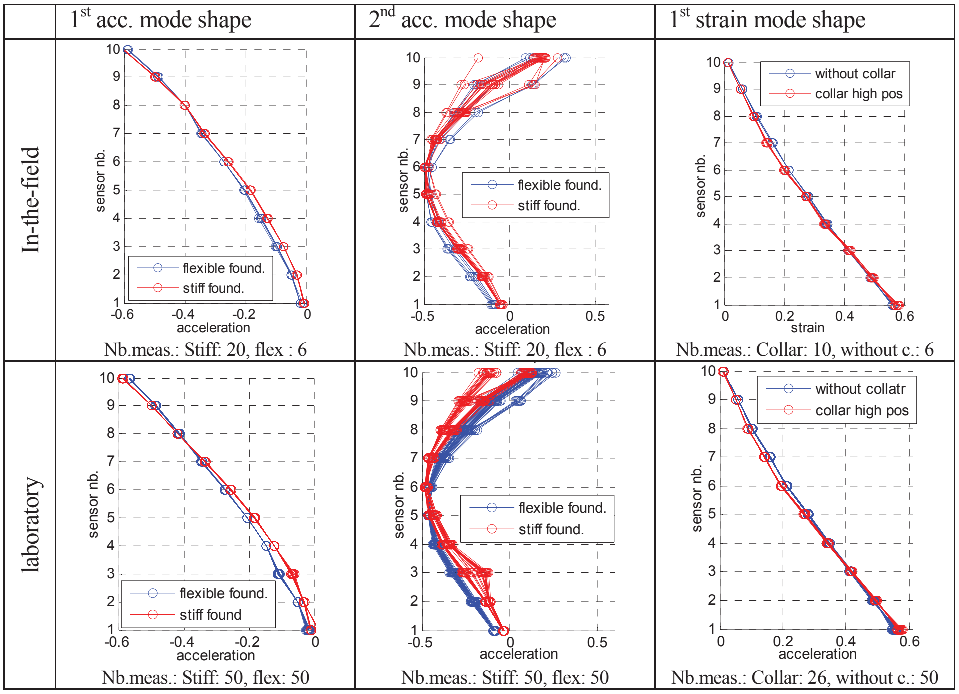

Figure 7: Examples of identified mode shapes from in-the-field and laboratory measurements

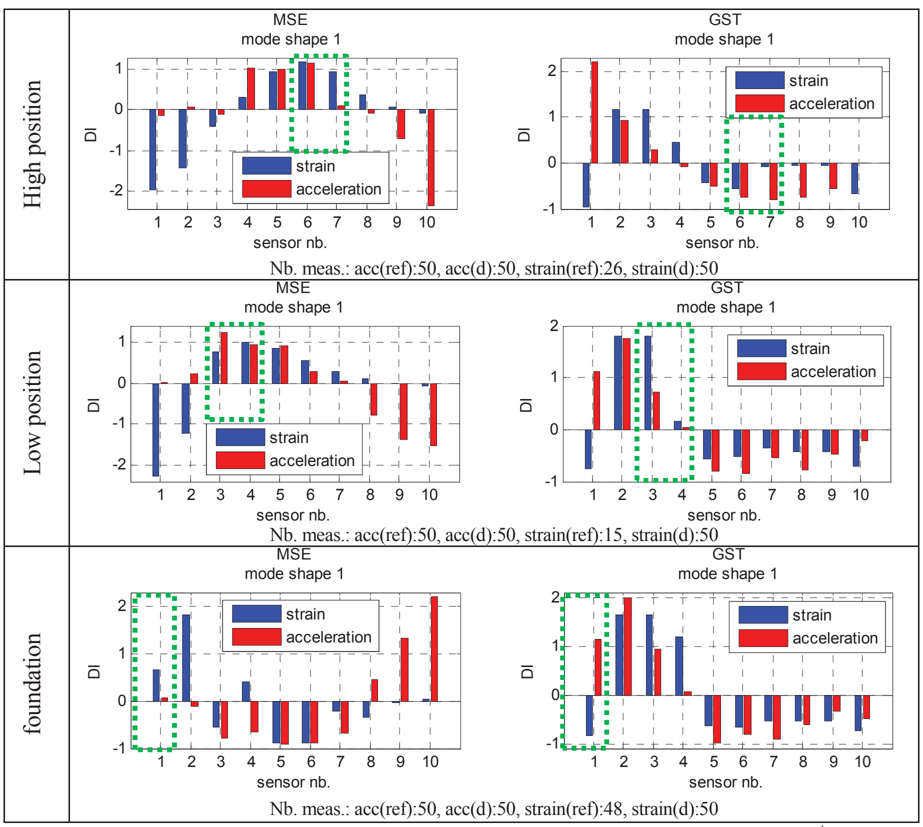

Figure 8: Resulting DI diagrams of the damage detection algorithms applied to the 1st mode shapes derived from laboratory measurements, dashed boxes indicate sensors adjacent to damages

acceleration data. Further, strain data indicates a change of the foundation stiffness by high DI values corresponding tothe lower end of the tower. In contrast to that, the proposed GST algorithm is not sensitive to the damage location. For both, strain and acceleration data, the DI diagrams reveal a similar pattern, regardless of the induced type of damage.

CONCLUSION

The intention of this work was to evaluate the sensitivity of two damage detection algorithms applied to OMA data. The OMA data was derived by a wind excited structure. A numerical prestudy showed that the proposed algorithms are capable to locate damage correctly based on both strain and acceleration data. However, it was demonstrated, that curvatures calculated from acceleration data have a high sensitivity to noise. The OMA algorithm applied to the structure yields highly reproducible mode shapes for the 1^{st} strain and acceleration mode shapes, regardless of the wind field characteristic. Using the Gapped Smoothing technique under the encountered conditions damage cannot be located. However, the Modal Strain Energy method is sensitive to damage location. Based on acceleration measurements damage along the tower of the structure can be located. In addition to that, a change of foundation stiffness can be located when strain data is used.

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REFERENCES

1. A. Friedmann, D. Mayer, M. Koch, T.Siebel, *Monitoring and Damage Detection in Structural Parts of Wind Turbines*, InTech2011 (www.intechopen.com), p.207-232, 2011
2. H. Sohn; C.R. Farrar; F.M. Hemez; D.D. Shunk; D.W. Stinemates; B.R. Nadler; J.J. Czarnecki; *A Review of Structural Health Monitoring Literature: 1996-2001*, Los Alamos National Laboratory Report,LA-13976-MS
3. Stubbs, N.; Kim, J.-T.; Farrar, C.R.: *Field Verification of a Nondestructive Damage Localization and Severity Estimation Algorithm*; Proceedings of IMAC XIII, 1995, p. 210-218
4. Ratcliffe, C. P.; *Damage Detection Using a Modified Laplacian Operator on Mode Shape Data*. Journal of Sound and Vibration 204 (3), 1997, p. 505-517
5. M. Radzienski, M. Krawczuk, M. Palacz, *Improvement of damage detection methods based on experimental modal parameters*, Mechanical Systems and Signal Processing 25 (2011) 2169–2190
6. R.P.C.Sampaio, N.M.M.Maia, J.M.M.Silva, *Damage detection using the frequency-response-function curvature method*, Journal of Sound and Vibration 226(5)(1999)1029–1042.
7. A. Friedmann , M. Koch, D. Mayer, *Using the Random Decrement Method for the Decentralized Acquisition of Modal Data*, Proceedings of ISMA2010, September 2010
8. J. Rodrigues, R. Brincker, *Application of the Random Decrement Technique in Operational Modal Analysis*, in Proceedings of the 1st IOMAC), Denmark, Copenhagen (2005).
9. R. Brincker, L. Zhang and P. Andersen, *Modal Identification from Ambient Response using Frequency Domain Decomposition*, in Proceedings of the 18th IMAC, 2000.
10. Pandey, A.K.; Biswas, M.; Samman, M.M.: *Damage detection from changes in curvature mode shapes*, In: Journal of Sound and Vibration 145 (2), 1991, p.: 321-332