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SUBSPACE-BASED DETECTION OF FATIGUE DAMAGE ON JACKET SUPPORT STRUCTURES OF OFFSHORE WIND TURBINES

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ABSTRACT

The paper describes the application of the Stochastic Subspace-based Damage Detection (SSDD) method on model structures for an utilization of this approach on offshore wind turbine structures. Aim of the study was therefore to analyze the usability and efficiency of the detection method as well as to determine an optimized set of parameter for realistic damage on support structures of wind energy turbines. Based on results of an experimental fatigue test on a steel frame laboratory structure a strategy for a numerical verification of the experimentally evolved damage detection was developed, utilizing a time integration approach to simulate the dynamic response. In a second step the identified modeling and computing methodology is used to numerically investigate the ability to detect damage in real size structural components of offshore wind turbines.

KEYWORDS : *Damage detection, Offshore wind turbines, Numerical response simulation.*

INTRODUCTION

Offshore wind turbines are exposed to strong loading as well as to harsh weather conditions. Reliable monitoring and assessment of the structural condition is therefore of strong interest by investors, operators and insuring companies. Besides the recording of loading and stress states for verification of design assumption it is primarily the early indication of structural damage which effects the benefits of online monitoring methodology. Because of the high failure consequences for structural components of wind turbines as well as because of the partial rough assumptions of the design process, the interest in monitoring of the load carrying structure of wind turbines is immense.

For that reason, several research activities have been performed at BAM to enhance the Stochastic Subspace-based Damage Detection method (SSDD) and to optimize parameters for an effective and robust SHM application on offshore wind turbine structures. Unlike common vibration utilizing methods the SSDD methodology does not explicitly identify and assess modal properties. Instead a statistical χ^2 -type test is used to analyze changes in the dynamic response of the system for their significance [1, 2]. Starting with analyzing a reference state of the undamaged structure a Gaussian type residuum is created. Within the subsequent observation of the structural state the residuum is recalculated and tested for significant changes by a statistical hypothesis testing. The method has been successfully applied to several laboratory and real application from different mechanical systems utilizing disciplines [3–5].

Since tests on real offshore structures are very expensive, a 2-step strategy including numerical simulations is adopted. In the first step a steel frame laboratory structure was used to test and verify the method in small scale as well as to validate a numerical model of the lab structure. With the so obtained modeling and computing parameters in a second step a numerical model of a real size structure is assembled and, using time integration analysis, a monitoring system based on the SSDD method was investigated.

Within the context of this paper the part of the numerical dynamic response simulation is covered.

1. SUBSPACE-BASED DAMAGE DETECTION ALGORITHM

The stochastic subspace-based damage detection algorithm as used in the here presented studies is generally based on the theory of system realization as described in [6]. But instead of extracting modal system parameters the investigated approach exploits a residual, which uses the left null space of a Hankel matrix, describing the system. The theory has been widely used in the last years and some different approaches have been developed. The introduced work uses covariance-driven Hankel matrix estimates and a non-parametric χ^2 -type test for damage detection [7, 8].

Let us consider a linear output-only dynamic system in the discrete state space description of the form:

$$\begin{aligned} x_{k+1} &= Ax_k + v_k \\ y_k &= Cx_k + w_k, \end{aligned} \quad (1)$$

where x_k represents the state vector with and y_k the measured output vector, both at time step k . A is the state transition matrix and C the observation matrix. The vectors v_k and w_k denote the state noise and measurement noise processes, which are assumed to be unmeasured Gaussian white-noise sequences with zero mean. The eigenstructure of the system in (1) is defined by:

$$A\phi_\lambda = \lambda I\phi_\lambda, \quad \det(A - \lambda I) = 0, \quad \phi_\lambda = C\phi_\lambda. \quad (2)$$

A block Hankel matrix $H_{p+1,q}$, filled with output covariance estimations $R_i = \mathbf{E}(y_k y_{k-1}^T)$ is defined as

$$H_{p+1,q} \stackrel{\text{def}}{=} \begin{bmatrix} R_1 & R_2 & \dots & R_q \\ R_2 & R_3 & \dots & R_{q+1} \\ \vdots & \vdots & \ddots & \vdots \\ R_{p+1} & R_{p+2} & \dots & R_{p+q} \end{bmatrix}. \quad (3)$$

The indices $p+1$ and q define the number of considered time shifts and should be chosen in dependence on the assumed system order n , i.e. $pr \geq n$.

In the initial undamaged state S^T is the empirical left null-space (kernel) of the Hankel matrix $H^{(0)}$ that holds the property:

$$S^T H^{(0)} = 0. \quad (4)$$

The kernel can be extracted by factorization of $H^{(0)}$, e.g. using singular value decomposition:

$$H^{(0)} = [U_1 \quad U_0] \begin{bmatrix} \Delta_1 & 0 \\ 0 & \Delta_0 \end{bmatrix} V^T, \quad (5)$$

where $S = U_0$ is the kernel and $\text{diag}(\Delta_1, \Delta_0)$ is a diagonal matrix, presenting the singular values in descending order, where the singular values in Δ_0 are considered as zero or close to zero. For the damage detection algorithm the kernel is computed only once from the initial system.

The residual vector ζ_N is defined as function of the reference matrix S^T from (4) and the Hankel matrix $H_{p+1,q}$ of the actual system built from the covariance estimates of the measured output:

$$\zeta_N = \sqrt{N} \text{vec}(S^T H_{p+1,q}). \quad (6)$$

It can be deduced from (4) that ζ_N has zero mean if changes of the system do not occur, and non-zero mean in the case of changes. Therefore, for the undamaged state the left null space of the Hankel matrix can be used as reference for future residual analysis. Under convenient assumptions, the residual function is asymptotically Gaussian. Then, it manifests itself to damage by a change in its mean value, also corresponding to an increase of the mean of the χ^2 -test statistics

$$\chi^2 = \zeta_N^T \Sigma^{-1} \zeta_N, \quad (7)$$

where Σ is the residual covariance

$$\Sigma = \mathbf{E} [\zeta_N \zeta_N^T]. \quad (8)$$

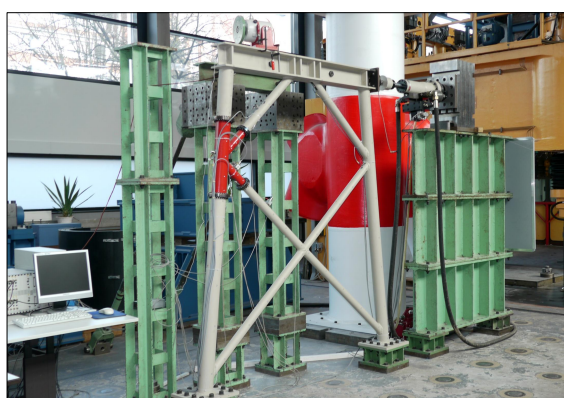
The monitoring of the system consists in calculating the χ^2 -test value on the Hankel matrices determined from newly recorded output data and comparing it to a threshold. A significant increase in the χ^2 -value indicates that the system is no more in the reference state.

2. LABORATORY FATIGUE TEST APPLICATION

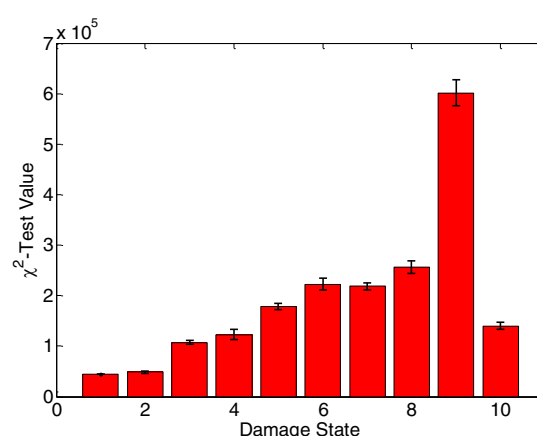
The laboratory steel structure represents a two-dimensional section of a jacket-type support structure of an offshore wind turbine with a scale of the general dimensions of approximately 1:10. Figure 1(a) shows the laboratory test structure with the loading unit in the testing facilities at BAM.

After extensive studies with defined damage by successive opening of a flanged connection a fatigue test was accomplished to test the applicability of the SSDD-method to real damage. Principally, the test procedure consisted out of two general and alternating tasks, the inserting of the fatigue relevant load cycles and the measurement of dynamic response series for determination of the χ^2 -value. The cyclic loading consisted of load series with a constant alternating horizontal force of ± 50 kN applied at the top girder of the structure with a frequency of 3 Hz. After completion of each load series a damage test was conducted. For the damage tests a broadband random signal with a frequency content between 10 Hz and 1000 Hz was produced by a shaker control unit and after amplification was induced via an electro-dynamic shaker at the top of the structure. For the vibration measurement, all in all 9 piezoelectric accelerometers were applied at the structure.

A total of 10 load series and therefore 10 damage states were implied. The result of the fatigue damage test is shown in Figure 1(b). The bars represent the mean of 10 to 30 tests executed in one damage state and the error bar represents the related variance. The diagram shows a continuous increase of the χ^2 -based damage indicator up the final load series, where a significant drop of the value is noticeable. The reason for this evolution is, that a first fatigue crack has evolved at one leg-footplate connection during load series 3 to 9. Due to stress redistribution in the last loading series a second fatigue crack developed at the other leg-footplate connection of the structure. While during progression of the first crack the modal system changed gradually with the effect of an continuous increase of the χ^2 -value, the second crack resulted in a distinct switch back of the modal system and a decrease of the χ^2 -value. A detailed description of the fatigue test and discussion of its result is given in [9].



(a) Laboratory model structure



(b) SSDD result of fatigue test

Figure 1 : Stochastic subspace-based damage detection during laboratory fatigue test.

3. NUMERICAL APPLICATION

To transfer the experimentally obtained results from the laboratory structure to real size foundation structures, a numerical simulation strategy is employed. It implies, that first the dynamic response of the structure under observation is simulated by transient (time integration) numerical analysis in an optimized complexity and secondly the so generated time series of deflection parameter are analyzed by the SSDD algorithm. Intention of the numerical studies is to analyze, to which extent this methodology is able to reproduce the effects of real structural damage to the dynamic response of the system and therefore, to which extent the numerical simulation is able to test the reliability and the sensitivity of the SSDD. Based on a successful application of the described approach the final objective is to configure an optimal measurement setup for monitoring real offshore wind turbine structures. The idea within this task is to verify and validate the numerical model of the lab structure on the results of the laboratory fatigue test to use these information for modeling a real offshore wind turbine structure.

The numerical analysis was carried out using the commercial FEM program system ANSYS in version 14.5 [10]. Accordingly, the modeling was conducted using the element types and meshing algorithms, available within ANSYS.

3.1 Laboratory model structure

In a first step it was analyzed, to which extent one is able to numerically reproduce the experimental results from the described laboratory test.

Modeling of lab structure: Based on preliminary studies for comparison of models with beam and shell elements hybrid modeling has been chosen utilizing beam as well as shell elements. The use of shell elements arose from the necessity for a high resolution modeling of the fatigue crack. All other parts and components of the laboratory structure as well as the entire support structure were modeled by beam elements. This approach ensures a corresponding limited number of degrees of freedom for a sufficiently accurate description of the global dynamic behavior of the structure. Concentrated masses (flanges, shaker) were modeled as lumped masses.

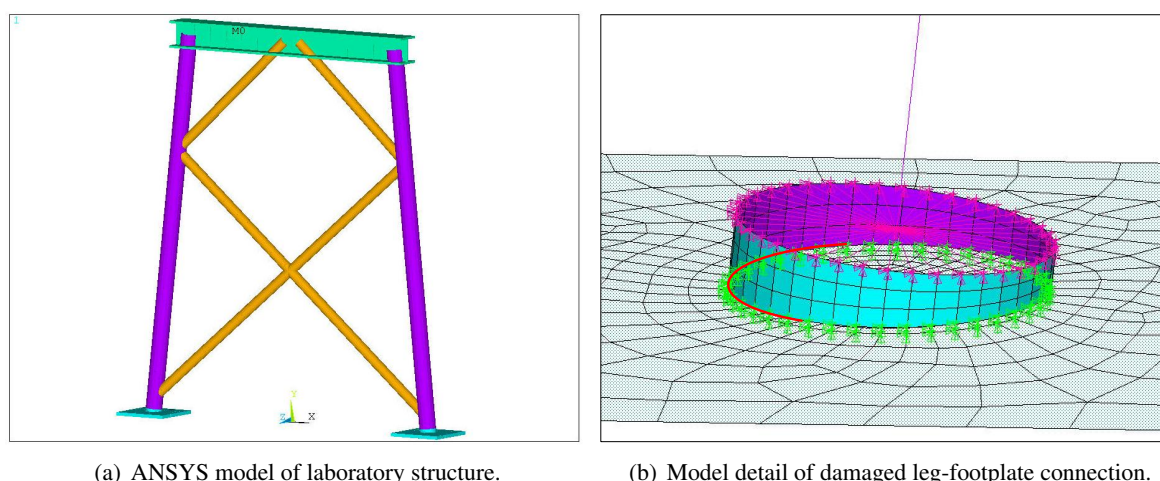


Figure 2 : Numerical model of laboratory structure.

The fatigue crack is modeled by successive elimination of neighboring nodal couplings between the legs and the footplates. For reasons of computational efforts the non-linear crack opening/closing behavior was not included into the modeling. The introduced simplification is well-known to the authors, but appraised negligible for the structural dynamic response. Figure 2(b) shows the region of

modeled damage with the coupling of the beam and shell elements of the leg (magenta) as well the coupling of the leg and footplate shell elements (green) which are successively eliminated for damage simulation.

The validation of the numerical model was done by modal analysis. The mode shapes of the numerical model were compared with those of an experimental modal analysis conducted on the laboratory structure. As comparative parameter the Modal Assurance Criteria (MAC) was used. First tests showed a general consistency in the modal values. A small necessary modification of the numerical model was conducted by the change in the support stiffness at the feet of the structure.

Transient analysis on lab structure: For obtaining the structural dynamic response of the system time series of accelerations were generated by a transient analysis using the described model as well as a time series of loading sequences on the base of Gaussian white noise. In each performed analysis 98 304 calculation steps were executed. Since the used load step frequency was 2500 Hz, each response data set consisted of 39.32 s simulated output accelerations.

Within the post processing the acceleration directions were transformed into the axes of the real sensors and finally were used as input in the SSDD algorithm. Due to the high computational effort of the transient analysis only a limited number of χ^2 -test values were calculated for each damage state, with the exception of the reference state where a considerable number of 30 tests were used for the residual covariance matrix.

Results and discussion: The resulting sequence of χ^2 -test values for the simulated fatigue damage propagation is shown in Figure 3. Compared with the results of the experimental fatigue test as displayed in Figure 1(b) it can be shown, that the χ^2 -values follow the same pattern. That applies also to the decrease of the damage indicator after appearance of the second fatigue crack, even though the decrease is not that distinctive than for the experimental obtained χ^2 -values.

So all in all it can be stated, that the numerical simulation is able to reproduce structural dynamic responses, comparable to those of the real fatigue test.

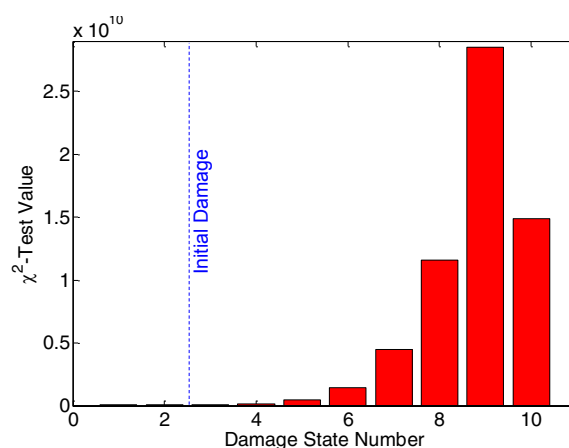


Figure 3 : χ^2 -value as damage indicator of simulated fatigue damage.

3.2 Jacket structure

In a second step the dynamic response of a real size jacket structure under progressive fatigue damage is simulated. Objective is to numerically analyze under which condition and to which extent a reliable detection of structural damage is possible under operational conditions at wind turbine structures.

Modeling of jacket structure: Generally, the same modeling principles as for the lab structure model are applied. In particular this concerns the element types, where with the exception of the damaged area, beam elements were applied. For reasons of high resolution for the double-K-joint with the simulated fatigue crack shell elements are used (see Figure 4). The successive damage itself is modeled by elimination of nodal couplings between shell elements. The model consists out of the jacket itself, the transition piece to the tower and the tower. The rotor-nacelle system is modeled as lumped mass on the top of the tower. All used dimensions are close to real ones.

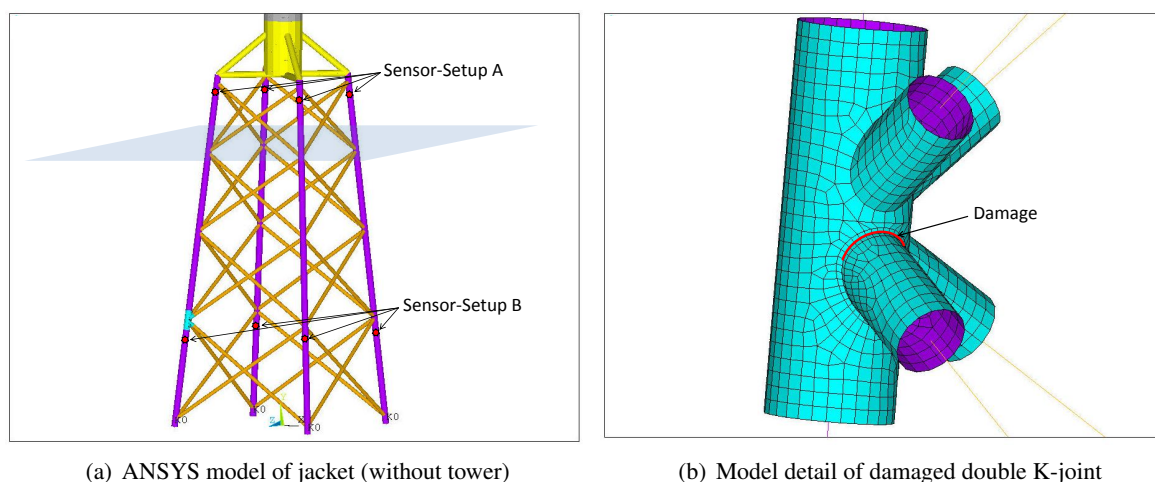


Figure 4 : Numerical model of jacket structure, (a) with additional information of the two analyzed sensor setups for the SSDD and (b) with additional indication of the damaged area.

Specific attention was directed into accounting for those boundary conditions which essentially influence the dynamic behavior of the wind turbine structure and therefore influence the damage detection result. This concerns mainly the loading process, the support conditions in the seabed as well as the damping characteristics of the dynamic systems. A major influence on the dynamic structural behavior and, thus, on the quality of the damage indication has the wind loading. To provide loading for the numerical simulation of the dynamic response, measured responses of a real onshore wind turbine are used. Strain-time signals were recorded on the top of the tower of the monitored wind turbine and processed to stress resultants which are used in the simulation as lateral and axial force input as well as bending moments acting on the top of the tower. In addition the so generated load time series are conditioned with white noise to emphasize the stochastic nature of wind. The described monitored time signals were also used to develop lateral load time series to apply on the tower structure, distributed over its length. Loading from waves and current as well as from turbine control operations are not considered.

Another considerable effect on the dynamic behavior results from damping. Besides the classic material and structural damping effects the damping from the bedded pile support and especially from the hydrodynamic and the aerodynamic damping have a major influence on the dynamic behavior of an offshore wind turbine structure. With the exception of aerodynamic damping the single parts of damping are taken into account as stiffness proportional damping, separately for the tower and the support structure. Due to the complexity of its modeling, aerodynamic damping was not accounted for. In succession it needs to be postulated, that the rotor is not moving during the damage detection tests and only load files measured at wind speed of less than 4 m/s were considered in the analysis. For modeling the support conditions, the horizontal and vertical stiffness parameter are determined by integration of the pile bedding constants.

Transient analysis for jacket structure: Similar to the analysis procedure of the lab model as described above the dynamic response of the system was computed and time series of output accelerations at defined locations were generated. For a later optimization of sensor number and location, output time series were produced for every element node of the model. To indicate the systems eigen-structure, a sampling frequency of 1000 Hz was applied for a time period of 60 s. So each record contained 60 000 acceleration samples for each channel. For each computation lasting approximately 12 h only a limited number of damage states were investigated. All in all 55 data sets were generated, 41 for the reference state and 14 for the seven states of progressive damage.

Damage detection test for jacket structure: Within the presented study two different sensor setups and at the same time two sampling frequencies were analyzed. In the sensor-setup A (see Figure 4(a)) four 3D accelerometer are installed near the upper end of the corner legs. This sensor layout is quite attractive for the operators of monitoring systems since the sensors lie above sea level which makes installation, maintenance and replacement significant easier. Of course, possible installations need to be protected against mechanical damaging from breaking waves. Secondly, the sensor-setup B as shown in Figure 4(a) contains four 3D accelerometer, which are installed on the four corner legs within the lowest jacket section, near the damage.

Regarding the sampling frequency, two different values were analyzed, first the “measured” $f_a = 1000$ Hz and secondly the down-sampled $f_a = 250$ Hz. The reason for the study is to examine the sensitivity of the χ^2 -test with respect to the necessary data volume.

Results and discussion: The results for two sensor locations are shown in Figure 5. Both figures show the χ^2 -values of the same simulated damage process, but analyzed in terms of SSDD for the two different sensor setups and the two sampling frequencies. To compare the χ^2 -values for both sampling frequencies, the result values are related to the mean of the reference state χ^2 -values in each analysis. For each damage state two records are analyzed. The utilized damage states are described in the legend of the diagrams as the length of the fatigue crack. Additionally, it should be mentioned, that the smallest damage with a crack length of $L = 260$ mm stays for a reduction of the bending stiffness of 2% and the largest included damage with a crack length of $L = 1299$ mm stays for a reduction of the bending stiffness of 91%. The threshold (dashed line) is defined as 1.5-time magnification of the 98% fractile of χ^2 -values in the reference state.

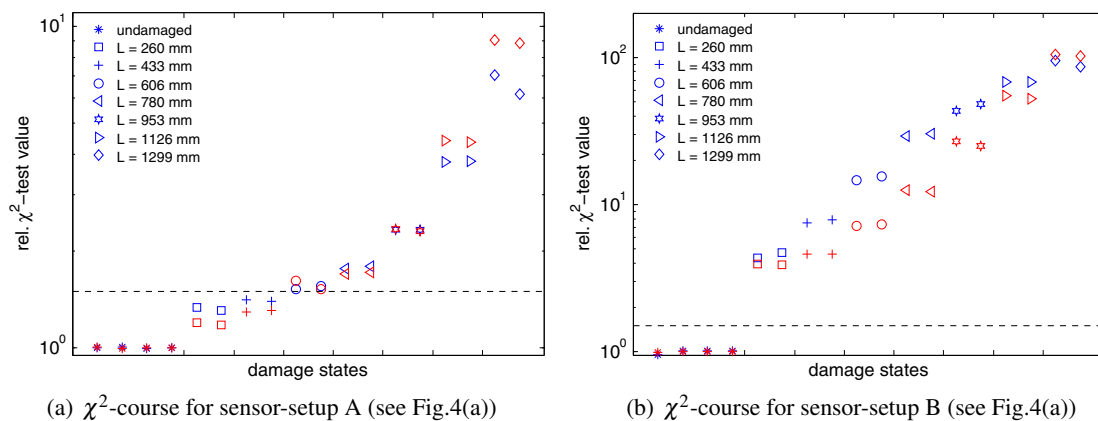


Figure 5 : SSDD on numerically simulated dynamic response of a jacket structure for two different sensor-setups and two sampling frequencies. Blue markers present the related χ^2 -values of the data set, recorded with $f_a = 1000$ Hz and the red markers the ones with $f_a = 250$ Hz.

In terms of the sensor layout it can be shown that the detection of fatigue damage in early stage is

possible with four 3D-accelerometer if the sensors are located in relative vicinity to the damage. For the sensors applied on the top of the jacket structure, a significant increase of the damage indicating χ^2 -value can be detected for a crack length of $L = 606$ mm, which is equivalent to a loss of bending stiffness of 22%.

Regarding the sampling frequency it is shown that a reduction of the amount of data to $\frac{1}{4}$ did not have any consequence to the quality of the damage indication. Our additional investigations showed, that a further downsampling does have a significant influence to the damage indicator.

CONCLUSION

With the overall objective to test the applicability and functionality of the stochastic subspace-based damage detection method on offshore wind turbine structures numerical analysis is used to simulate the dynamic response of the structure. On the base of experimentally achieved detection results from a laboratory structure numerical modeling and computing approaches were developed and tested. In a second step the optimized numerical analysis methodology is applied on a “virtual” real size jacket structure of an offshore wind turbine. With the simulated responses of a structure in undamaged and damaged states the SSDD algorithm is utilized for investigations about several sensor location setups as well as on the influence of the sampling frequency.

Taking into account some simplifying assumptions the application of SSDD methods on numerically produced response data sets showed a respectable sensitivity of the χ^2 -value-based damage indicator. Though not detectable in early stage, typical fatigue cracks in welded joints of support structures have a significant impact to the indicator for a remaining bending stiffness of the damaged component of app. 80%.

Future activity in this field should focus on a realistic modeling of the dynamic response influencing time-variant processes like wind and wave loading as well as the aerodynamic damping.

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