Dimensionality Reduction of Active Vibration Data for Detection and Monitoring of Progressive Damage in Wind Turbine Blade

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ABSTRACT

The present work considers the use of an active vibration monitoring system for wind turbine blade SHM. A test campaign is conducted with a 52-meter commercial wind turbine blade, investigating the potential for detection and monitoring of damage using the active vibration monitoring system. A crack is manually induced in the shear web laminate of the wind turbine blade, and progressive damage propagation is obtained during fatigue testing.

INTRODUCTION

Towards high availability of wind energy, and thus reduced energy prices, the use of structural health monitoring (SHM) systems for early detection of damage in wind turbine blades is becoming increasingly relevant. Various sensing modalities have been investigated for use in blade SHM [1, 2]. Vibration-based sensing systems are commonly used in the context of SHM. Systems relying on low-frequency vibrations, e.g. lower-order natural vibration modes of structures, have proven useful for global damage detection. However, for large structures, such as modern wind turbine blades, damages need to reach a significant size before they affect the modal parameters of the structure [3]. On the other hand, high-frequency vibration systems, such as acoustic emission systems, enable detection of very small damages, but requiring a high number of sensors to cover large structures [4]. To obtain a compromise between detectable damage size and monitoring range, the use of the medium-frequency range has been investigated [5], proving useful for detection of small damages in a large wind turbine blade.

Thus, the present work seeks to build on the existing research on medium-frequency SHM systems through design and testing of an active vibration monitoring system for

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Figure 1. Wind turbine blade mounted on test stand at Siemens Gamesa Blade Test Center in Aalborg, Denmark.

wind turbine blade SHM. Actuation in the medium frequency range is applied, and the measured vibration output is characterized by the power spectral density (PSD). Principal component analysis (PCA) is used for dimensionality reduction and to increase robustness to operational noise. Finally, outlier analysis is performed through use of the Mahalanobis distance, enabling characterization of initiation of damage as well as gradual damage progression. This work is based on previously published papers by the authors [6–8].

WIND TURBINE BLADE TESTING WITH PROGRESSIVE DAMAGE DEVELOPMENT

A 52-meter commercial wind turbine blade was used for the test campaign, shown in Figure 1. The purpose of the test campaign was to introduce multiple different damages in the blade sequentially, perform flapwise fatigue testing to propagate the damages, and use various sensing systems to collect data. Ultimately, opportunities and limitations of the different sensing systems in blade SHM were desired to be determined. The present paper documents one of the investigated damage cases and the used active vibration monitoring system. More details are included in [6–8].

The damage in question is a laminate crack, introduced in the shear web of the wind turbine blade, see Figure 2. With an increasing number of fatigue cycles, the crack grew towards the spar cap laminate (i.e. towards the top of Figure 2). Multiple delamination fronts developed around the crack, see Figure 2(c-d).

ACTIVE VIBRATION MONITORING SYSTEM

The active vibration monitoring system used, shown in Figure 3, consists of an electrodynamic shaker, a force transducer, and 11 uniaxial accelerometers. All parts of the active vibration monitoring system are mounted with the active direction perpendicular to the surface of the blade laminate. The layout of the active vibration monitoring system is shown in Figure 4, with the vibration shaker being placed on the shear web laminate.

The used shaker was set to apply active vibration excitation through a logarithmic chirp at frequencies between 100 and 3,000 Hz. Thus, this SHM system was targeting the medium-frequency range, attempting to obtain a compromise between detectable

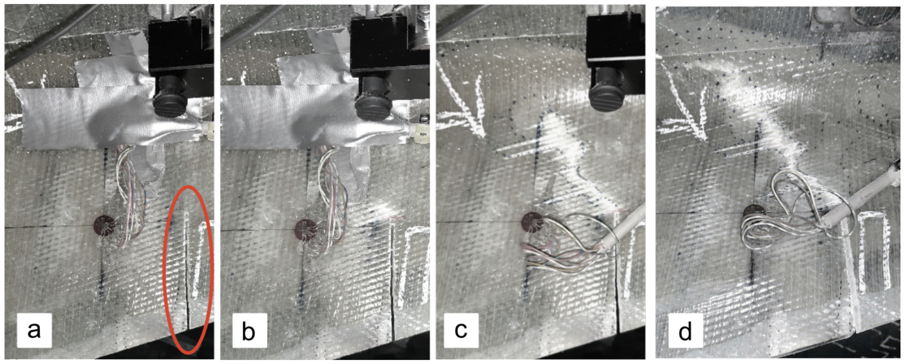

Figure 2. Manually induced shear web crack circled in red (a), and damage propagation over the course of the performed fatigue test (b-d).

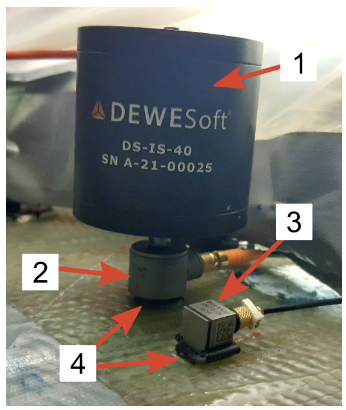

Figure 3. Electrodynamic vibration shaker (1), force transducer (2), piezoelectric accelerometer (3), and mounting plates (4).

damage size and effective monitoring range [7].

Using the active vibration monitoring system, data was collected periodically over the course of the performed fatigue test. Data was collected during stand-still, i.e. when the fatigue test was not running, and during fatigue testing. Thus, data was obtained in two different operational states, with different levels of noise affecting the vibration measurements.

SIGNAL PROCESSING

A total of 5,471 observations were recorded with the active vibration monitoring system, of which 3,076 were in the healthy state and 2,395 were in the damaged state. To facilitate classification of the health state of the blade, the PSD was chosen. Based on operational noise and signal-to-noise ratio considerations, the frequency range was trimmed to 600 - 2,500 Hz. Further dimensionality reduction was obtained by use of PCA, using principal components (PCs) explaining 95% of the variance of the original data. An added benefit of using PCs as features proved to be added robustness to changes in the operational state, i.e. differences in the dynamical behavior during stand-still and fatigue testing. To classify the health state of the blade, the Mahalanobis distance is used

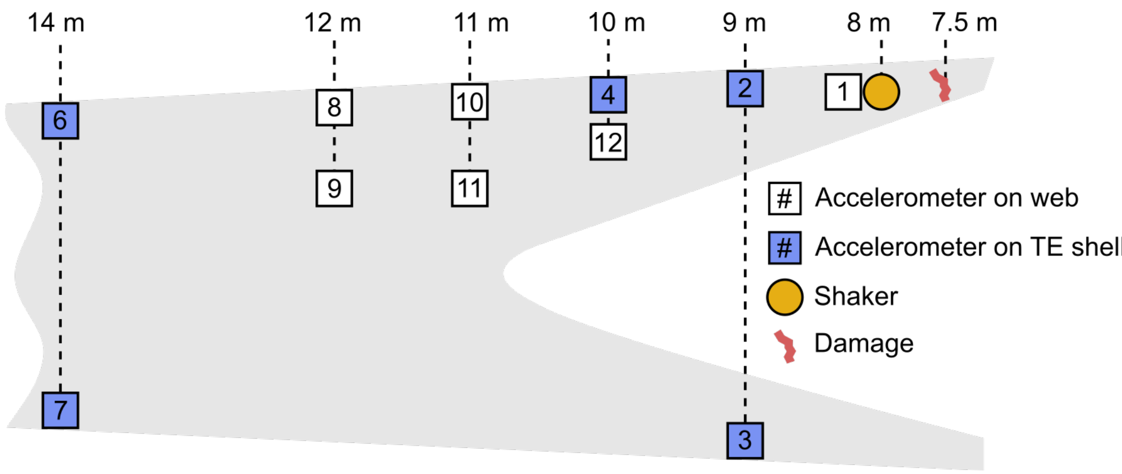

Figure 4. Placement of sensors on the shear web and trailing edge (TE) shell panel.

as a damage index:

$$D_i = \sqrt{(y_i - \overline{X})^T S^{-1} (y_i - \overline{X})} \tag{1}$$

where y_i is the i$^{\text{th}}$ observation of the testing data set Y, in which potential outliers are searched for, $\overline{X}$ is the mean of the training data set X, and S is the covariance of the training data. To calculate the healthy threshold value, the approach proposed in [9] is used. Every second observation for the first 90% of healthy observations were used for training of the healthy threshold, and the remainder of healthy observations were used for testing. This approach was chosen to account for fluctuations in the applied fatigue loading. More details regarding signal processing of the recorded active vibration data can be found in [7, 8].

RESULTS AND DISCUSSIONS

The PSDs for all observations recorded in the healthy state of the blade and with the shear web crack shown in Figure 2 are plotted for the 11 accelerometer channels in Figure 5. PSDs for observations in the healthy state are colored green, and observations in the damaged state are colored from yellow to red with increasing damage severity. As can be seen from e.g. the plot of Sensor 11, clear changes can be observed between the healthy (green) PSDs, including changes with increasing damage severity. Thus, the PSDs from the accelerometer signals are deemed to be sensitive to both initiation and progression of the investigated shear web crack.

Using features corresponding to the PCs explaining 95% of the variance of the PSDs for each individual sensor channel, the Mahalanobis distance D is calculated and plotted in Figure 6. The healthy threshold value for each channel is marked by a horizontal line, and the point of damage introduction is marked by a vertical dotted line. Generally, above 99% of the healthy testing observations fall within the healthy threshold. Immediately following introduction of the shear web crack, a jump in the damage index D can be observed for all sensor channels. For e.g. Sensor 7, gradual increase of the damage index in line with damage progression can be observed. This is however not the case

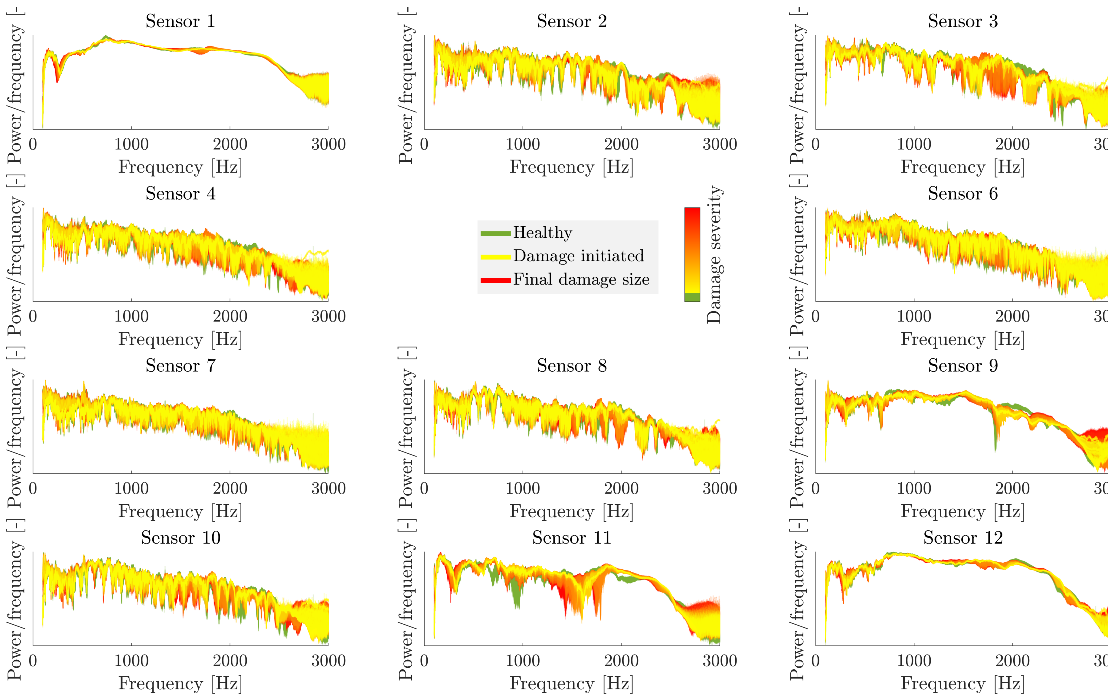

Figure 5. Power spectral densities (PSDs) for all accelerometer channels.

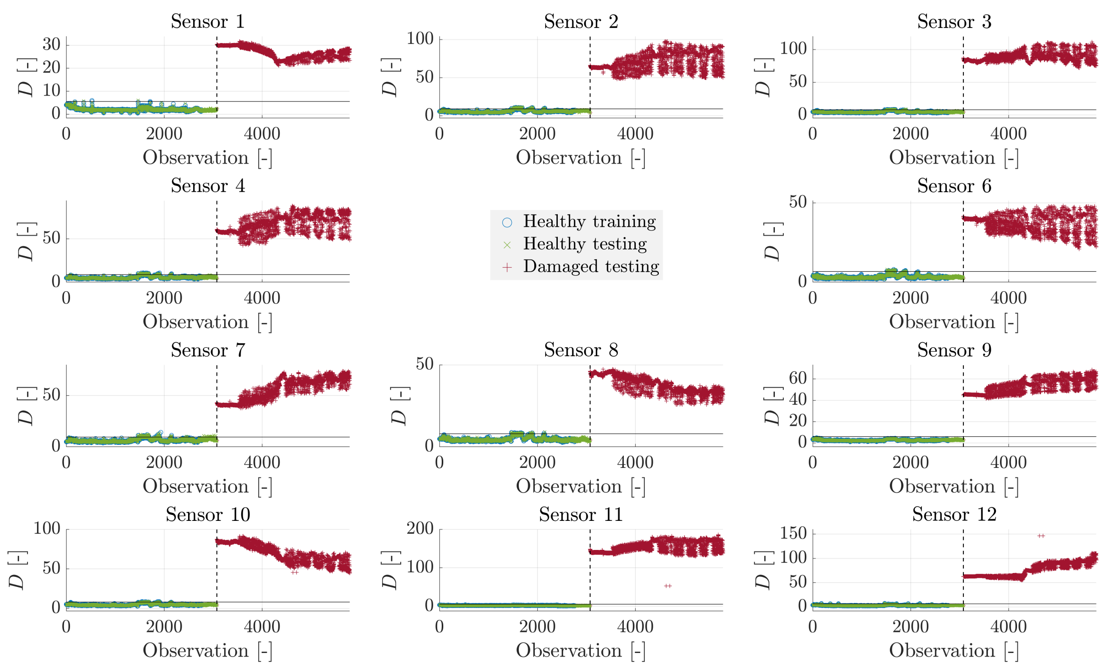

Figure 6. Outlier plots for all accelerometer channels.

for all sensor channels, where some of them show decreasing magnitude of the damage index with increasing damage severity. More results can be found in [7, 8].

CONCLUDING REMARKS

An extensive test campaign was conducted towards SHM of large wind turbine blades, using a 52-meter commercial blade. The present work presented one of the damage cases investigated, including the use of an active vibration monitoring system designed for blade SHM. Frequency sweeps were applied to the blade in the medium-frequency range, allowing for the detection of the initiation of a small crack, as well as gradual damage development over time. Furthermore, the SHM system enabled correct classification of the health state of the blade in two different operational states, thus proving to be robust to external noise. Towards the practical application of such SHM systems for wind turbine blades, further research in accounting for operational and environmental variations would be of value.

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