Acousto-Ultrasonic Damage Monitoring in a Thick Composite Beam for Wind Turbine Applications

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Abstract
Monitoring of wind turbine components is more and more important to guarantee a safe and efficient operation of these systems, in particular when off-shore wind turbines are considered. Fatigue is a dominant failure mechanism and therefore a critical design parameter. Earlier research of the authors revealed that one of the critical components in a wind turbine blade is the spar cap. Failure of it is detrimental for the functioning of the wind turbine and can lead to an accumulation of failures and to an increase in the wind turbine operation and maintenance cost. Fatigue is often detected based on a stiffness reduction of the component. A common problem observed in monitoring systems based on stiffness reduction is that the damage accumulates without causing an observable change of stiffness. As a result, the response time between stiffness drop and component failure is relatively short. An alternative monitoring method, based on acousto-ultrasonics (AU) is proposed, allowing for damage accumulation monitoring. The method is based on the Reconstruction Algorithm for Probabilistic Inspection of Damage (RAPID) as applied to thin-walled (composite) structures to identify damages such as cracks and delaminations. The suitability of this damage identification method for a thick-walled glass fibre beam, representing a spar cap, was tested by the authors. Based on the positive outcome, a similar beam was equipped with eight piezo-electric transducers and subjected to a three-point bending fatigue test. The bending stiffness is measured using the force and displacement of the test bank and at regular intervals, an AU measurement is executed. In a mutual comparison of the measurements, it is shown that the AU measurements are sensitive to damage accumulation, whereas the stiffness measurement is not. The newly proposed method thus allows for a much earlier warning of imminent failure and can be used for prognostics and improved maintenance planning.

Keywords: Wind turbine, acousto-ultrasonic, damage accumulation, thick composite

1. Introduction
Over the past years, the wind energy sector has grown significantly. The need for green energy to meet climate targets and the positive investment returns has pushed the development of off-shore wind farms in particular. The industry has focussed on the development of larger wind turbines, which negatively affects the operations and maintenance cost in case of failure. According to Wilkinson et al. [1], the operational and maintenance costs of offshore wind turbines are five times as high as those of their onshore counterparts. An important factor in these costs are the higher failure rates that are reported [2, 3].
The rotor blades of a wind turbine, mostly made of glass fibre reinforce plastic, belong to the critical parts of the system. Failure of a blade does not only result in a loss of energy production, it can easily induce a chain of damage in the wind turbine, up to a complete collapse, or even damage nearby placed wind turbines. Damage, occurring during operation, can be categorized in accidental and structural damage [4]. Accidental damage can be caused by the environment, such as rain droplets causing erosion on the leading edge of the rotor blade. The structural damage can be caused by the cyclic loading of the system (fatigue loading). Blades, mostly made of glass fibre reinforce plastic, are therefore designed using fatigue criteria. Composites under fatigue loading develop micro-cracks, transverse cracks, typically in the fibre bundles, or at the bundle interface. These cracks initiate stochastically in time and space and grow as the loading continues. Micro-cracks join or increase their grow rate on layer interfaces until they formed a delamination. This results in a significant drop in structural integrity and a functional failure of the component, possibly without any visual indication.

The objective of the “TKI Wind op Zee” SLOWIND (Topconsortia for Knowledge and Innovation - Wind at Sea, Load and Structural Health Monitoring of Offshore wind turbine blades) project is to make maintenance more predictable, based on measurements of physical quantities. Clearly, damage accumulation is an important parameter to monitor to allow for the prediction of the remaining useful life of wind turbine components. An initial investigation into the failure mechanisms of wind turbine blades [4], revealed that, amongst a few others, fatigue in the spar cap is a common failure mechanism with a significant effect on the structural integrity, hence the functionality of the blade. The problem in this case is to determine the damage accumulation during service. Current practise is to execute for example a three point bending fatigue test on a test object, representative for the final structure. The force is measured for a given displacement amplitude during the measurement. Typically, the force-displacement relation is not affected strongly by the damage accumulation up to close to the moment the structure fails: the global bending stiffness is not affected by the small cracks growing in the interior of the material.

The method adopted by the authors, is based on the use of PZTs on plate-like (thin) composite structures [5] to identify a delamination. Here, the method will be applied on a thick composite structure. Delaminations can be caused by fatigue or impact. The latter is of interest for thin, skin-stiffener structures [6, 7] as frequently applied in the aviation industry: a highly reliable assessment must be made whether the structure is safe to be used, or not, in which case an inspection is needed. Such a monitoring system effectively replaces (time-consuming and thus costly) visual inspection. Impact are however inherently unpredictable. Here, the method will be used to monitor the damage accumulation due to fatigue and resulting in (fatal) delamination of the structure.

2. Method

The PZTs, in this area of research often referred to as Piezoelectric Wafer Active Sensor (PWAS), are bonded on the structure and are activated with short burst signals in the low ultrasonic frequency range (\(\sim 10\) kHz–\(\sim 100\) kHz), resulting – for thin structures – in shear-horizontal (SH) and shear-vertical (SV) guided waves. The term “Acousto-Ultrasonics” is used for this type of ultrasound signals. A network of PWAS is formed (Fig. 1), where each transducer is sequentially appointed as actuator, while the others act as sensor. A set of signals from PWAS \(i\) to PWAS \(j\) is thus acquired. Using the Reconstruction Algorithm for Probabilistic Inspection of Damage
(RAPID) [8], the location of a damage, including size, can be estimated. This method is successfully applied for thin, plate-like structures [6,7,9], the application of the Acousto-Ultrasonic technique for thick structures is however less investigated. The present study therefore investigates the use of this method in thick composite structures.

![Figure 1](network.png)

**Figure 1**: Network of Piezoelectric Wafer Active Sensors (PWAS). Each PWAS is sequentially assigned as actuator, while the others act as receivers.

The RAPID algorithm is based on the comparison of the signals of each of the actuator-sensor paths in pristine and post-damage state. A difference between these two signal does not indicate a location yet, as the difference is condensed to a single number – the damage index $\rho_{CC}$. Typically, the correlation coefficient between the two signals $S$ is used as damage index [10, 11]:

$$
\rho_{CC,k} = \frac{\sum_{k=1}^{N} (S_{H,k}S_{D,k}) - \sum_{k=1}^{N} (S_{H,k})\sum_{k=1}^{N} (S_{D,k})}{\sqrt{\sum_{k=1}^{N} (S_{H,k}^2) - (\sum_{k=1}^{N} (S_{H,k}))^2} \sqrt{\sum_{k=1}^{N} (S_{D,k}^2) - (\sum_{k=1}^{N} (S_{D,k}))^2}} \tag{1}
$$

The subscript $H$ refers to the (healthy) reference state, $D$ to the current, potentially damaged state and $k$ to the actuator-sensor path number. A range of alternative methods is available that can be used to calculate the damage index [6,12]. The choice of the method depends on the application. Venterink et al. [13] concluded that the Signal Amplitude Squared Percentage difference algorithm (SAPS), with a small modification with respect to the original formulation provided the best results for this particular case. The algorithm for the damage index value $\rho$ is defined as (using the same symbols as in (1)):

$$
\rho_{SAPS,k} = 1 - \left( \frac{\max (S_{H,k}) - \max (S_{D,k})}{\max (S_{H,k})} \right)^2 \tag{2}
$$

The current signal $S_D$ will be equal to the reference signal $S_H$ if no damage is present, resulting in a damage index equal to unity, in line with the definition of the correlation coefficient in (1). The modification suggested by Venterink et al. [13] concerns the selection of the maximum peak of the current signal $S_D$: the maximum peak is taken from a small time range $\Delta t$ around the time of the maximum peak in the reference signal $t_H^{max}$, which yields the damage index $\rho_{SAPS}$ given by:

$$
\rho_{SAPS,k} = 1 - \left( \frac{\max (S_{H,k}) - \max (S_{D,k}^\tau)}{\max (S_{H,k})} \right)^2 \tag{3}
$$
with:

\[ S_{D,k}^* = S_D \left( t_{H}^{\text{max}} - \Delta t : t_{H}^{\text{max}} + \Delta t \right) \]  

(4)

The small time span is taken as the time duration of two oscillation cycles of the actuation frequency.

Subsequently, a probability function is used that indicates the probability that an anomaly at location \((x, y)\) has caused the difference between the signals \(S_H\) and \(S_D\). It uses a geometrical function \(R(x, y)\), specifying the geometrical distance from point \((x, y)\) to the direct line between the two transducers \(i\) and \(j\), ceiled by the threshold value \(\beta\):

\[
R(x, y) = \begin{cases} 
\sqrt{(\Delta x_i + \Delta x_{ij})^2 + (\Delta y_i + \Delta y_{ij})^2} + \sqrt{(\Delta x_j - \Delta x_{ij})^2 + (\Delta y_j - \Delta y_{ij})^2} & \text{for } R(x, y) < \beta \\
\beta & \text{for } R(x, y) \geq \beta 
\end{cases}
\]  

(5)

\[
\Delta x_k = \alpha(x - x_k), \quad \Delta y_k = \alpha(y - y_k) \quad \text{with } k = i, j; \quad \Delta x_{ij} = x_i - x_j
\]

where \((x_i, y_i)\) and \((x_j, y_j)\) indicate the locations of transducer \(i\) and \(j\) respectively. Typically, \(\beta\) is equal to 1.05, but \(\alpha\) and \(\beta\) can be optimised based on minimisation of blind zones, deviation in probability distribution values and the kurtosis [14].

Overlaying all path results gives a probability intensity map of the a possible damage. The damage intensity probability \(I\) at an arbitrary position \((x, y)\) is given by:

\[
I(x, y) = \sum_{k=1}^{N_p} \left((1 - \rho_k) \left( \frac{\beta - R(x, y)}{\beta - 1} \right) \right)
\]  

(6)

with \(\rho_k\) being the damage indicator of the \(k^{\text{th}}\) actuator-sensor path, \(N_p\) the number of paths.

3. Three Point Bending Experiment

The experiment executed by the knowledge center for Wind turbine Materials and Constructions (WMC) is a three point bending fatigue test of a thick composite beam. The uni-directional, 96 layer non-crimp glass fibre fabric reinforced plastic (Hexion RIM 135) beam was manufactured by WMC, yet instrumented by the University of Twente. The dimension of the beam are \(l \times b \times h = 900 \times 60 \times 56 \text{ mm}^3\). Eight transducers, four on top and four on the bottom, were bonded on the structure, centered around the mid point of the beam, as shown in Fig. 2.

The data acquisition system is based on a NI CompactRio system with a relay unit and an external signal amplifier. The system is shown in Fig. 3. The DC power supply is connected to the ADA4870 evaluation board amplifier from Analog Devices. The signal from the function generator is connected to the input of the amplifier, which output is connected to the relays. The relays has eight outputs, each directly connected with a transducer and an input channel of the NI CompactRio system. Hence, it is possible to automatically assign all PWAS sequentially as actuator, without having to (manually) rewire the transducers to the data acquisition system.
Figure 2: Schematic representation of the three-point bending test on the PZT instrumented glass fibre reinforced beam. The transducer locations are marked along with their number. The marked read areas indicate the expected locations of the fatigue damage. The three black circles in the side view are the plunger (top one) and the two supports of the three point-bending setup.

Figure 3: A schematic overview of the measurement setup with the NI system and the ADA4870 amplifier.

The LabVIEW program controlling the acousto-ultrasonic measurements was configured to communicate with the WMC system controlling the fatigue test. A schematic of the control is shown in Fig. 4. The fatigue test is paused at pre-defined intervals, shortening with increasing number of total cycles, to allow the acousto-ultrasonic measurements to be executed. Once these are finished, the fatigue test continues. It was estimated that the beam would at least sustain a total number of 1,000,000 cycles, prior to failure. The fatigue test was paused every 2,000 cycles until a total of 950,000 cycles was reached, after which the acousto-ultrasonic measurements were done every 1,000 cycles. The beam finally failed after nearly 2.7 million cycles. Initially, measurements during the fatigue cycle were scheduled as well (see Fig. 4), but these were not executed due to an unexpected shift of the signal, requiring different settings for the sensitivity.

A sampling frequency of 10 MHz is used, while the measuring time is limited to 1 ms, which is more than sufficient given the distance between the transducers and the wave
propagation velocity. Each measurement is repeated 10 times, after which the responses are averaged to reduce the noise level. A sensor sensitivity of 0.2 V together with a 14 bits resolution results in sufficient accuracy when studying the sensor signals. The maximum output voltage of the NI system is 10 V. The transducers have an operating range from -100 V to 400 V. The output for lower frequencies is sufficient but at increasing actuation frequency it seemed that the NI system cannot provide sufficient power to reach the desired output of 10 V. To overcome this power restriction problem, the ADA4870 evaluation board from Analog Devices is used. This amplifier is capable of enhancing the maximum output from 10 V to approximately 18 V with a sufficiently high slew rate. The maximum amplified output is still frequency depended but the variance decreases a lot. In an earlier experiment, a sweep of the excitation frequency was done, revealing 200-240 kHz to be a suitable frequency range for the actuation signal. The transducers exhibit an increased impedance in this frequency range, which is beneficial for energy transmission into the structure [5]. The excitation signal is a short, Hanning windowed burst signal of 3.5 cycles. More energy will be transmitted into the structure for longer actuation signal, resulting in a stronger response, yet also complicate the wave forms due to signal overlap of transmitted and received signal. A shorter actuation signal will not result in a sufficiently strong response signal.

4. Results & Discussion

The exact nature of the waves generated by the actuation signal will not be studied here. It is well known that lamb waves propagate in thin plate like structures, but the ultrasonic waves in a thick (steel) structure are more complex [15, 16]. The usage of composite materials in the present work will further increase the complexity. It will however be shown that a detailed understanding of the wave forms is not necessary. However, it is interesting to note that the time delay between the signals of PWAS 5 and 8 (see Fig. 2)
has nearly completely reduced if PW AS 1 is actuating. The difference in path length from PW AS 1 to 5 and that from PW AS 1 to 8 would suggest a longer delay. This indicates the wave field predominantly propagates in longitudinal direction of the beam, similar to the wave propagation in thin plates.

The time signal using a 200 kHz actuation signal and PWAS 1 as actuator, is shown in Fig. 5. This signal served as the reference state. The very first signal is not used, due to some start-up issues. The time signal used is the one after the first pause. It can be reasonably assumed that no fatigue damage has yet occurred after this low number of cycles.

The signals are expected to change once damage starts to accumulate. Hence, the signals of all subsequent measurements are compared to this reference state, using equation (3). The colour refers to the measurement number, where the darkest blue corresponds to the first, reference, measurement and most yellow to the last measurement before failure (approximately after 2.65 million cycles).

The damage index evaluation as a function of the number of fatigue cycles shows clear drops for some of the actuator-sensor pairs, implying the waveform is gradually changed. The damage index is expected to either stay constant or decrease, but it increases for higher cycle numbers in some cases, e.g. on the path from PWAS 1 to PWAS 4 (Fig. 6a). These artefacts are attributed to the complexity of the waveforms and the interaction with damage.

Figure 6: The DI values of using SAPS2 and an actuation frequency of 200 kHz. The colours refer to the measurement number. The first dark blue one is the reference measurement and the last yellow one is the last measurement prior to failure (approximately after 2.65 million cycles).

Although the damage index graphs do provide an indication of the damage, a clear estimation of the location cannot be derived from these graphs. To this end, the damage probability (RAPID) maps are constructed, using equation (6). The result, again for an actuation frequency of 200 kHz, is shown in Fig. 7. The figure shows three case: the damage probability map after 87,000 cycles, after 2,476,000 cycles and after 2,652,000 cycles – just before failure. The red lines indicate the location of the transducers. Clearly, the intensity of the damage is growing with increasing number of fatigue cycles. Note that the colour scale is different for the three images in Fig. 7. As expected, the damage starts to accumulate directly underneath the center punch. A minor asymmetry in the damage accumulation is observed: the area left of the center, between PWAS 2 and PWAS 6 appear to contain more damage than the area to the right of the center (PWAS 3 and PWAS 7). This is not unexpected, bearing in mind that the damage onset, the formation of the first cracks in the composite material, is stochastic. Small material inhomogeneities may trigger a micro crack to be formed. The inhomogeneous distribution of micro cracks further increases the inhomogeneity as cracks are more easily formed in areas with a high density of micro cracks.

To follow the damage accumulation over time, the probability maps need to be converted to a single number, representing the intensity or severity of the damage accumulation. There are several options for this, all building on some form of arbitrariness. Taking the maximum value does not reflect the sharpness of the peaks and the location of the maximum can change over time. Taking the affected area as a measure, requires the use of a threshold, for which no physical motivation can be given and which may have to be set dynamically as damage probability values can vary from case to case. Initially, the
maximum damage probability value is taken, leading to the graph shown in Fig. 8. The maximum of the damage probability value shows a sharp increase during the first 100,000 cycles. This is attributed to damage directly inflicted by the test fixture. A region with a relative constant slope then follows. This indicates a steady growth of damage inside the beam. Based on Fig. 7, this damage is formed in the center of the beam, just underneath the punch, yet slightly to the right. Standard ultrasonic testing can be used to verify the existence of damage in this region, but this was not possible during these measurements. The variation in slope of the maximum damage probability value between 100,000 and 2,300,000 cycles is attributed to both the stochastic nature of crack formation and the data processing method. Analysis of the data revealed that variations in the signal strengths can cause small variations. It is suggested to correct the damage index value with a scaling $C$ depending on the amplitude over noise:

$$C_i = \frac{\mu_k}{\mu_i} \frac{A_i}{A_k} \mu_i$$

(7)

where the index $i$ refers to the signal being corrected, the index $k$ to the signal that has the

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**Figure 7**: The damage probability (RAPID) maps, based on the SAPS algorithm and an actuation frequency of 2000 kHz, after a: 87,000 cycles; b: 2,476,000 cycles; and c: 2,652,000 cycles. The red lines indicate the location of the transducers.
maximum amplitude $A$ and $\mu$ equals the noise level. Assuming the noise level is the same for all signals, the scaling reduces to:

$$C_i = \frac{A_i}{A_k}$$

(8)

This also explains the negative slope of the maximum damage probability value between 2,300,000 and 2,500,000 cycles: the slope becomes positive after applying this correction. Although the slope of the curve is fairly constant, it appears to show some small jumps around 500,000 and 1,000,000 cycles, followed by a larger jump around 2,300,000 cycles. This last jump seems to be preceded by a small increase in the slope. Sound evidence is missing, by the lack of ultrasonic inspection of the beam after each acousto-ultrasonic measurement. However, a plausible explanation is the a jump represents the formation of a delamination. Photos of the beam, taken at different moments in time, reveal a delamination is formed, just underneath the top surface and roughly running from PWAS 3 to PWAS 2, as shown in Fig. 9a. Finally the beam failed due to a larger delamination in this area (Fig. 9b).

5. Conclusions

It is demonstrated with this experiment that acousto-ultrasonics can be used to follow the damage accumulation in a thick glass fibre reinforced beam. However, it should be noted that the curve does not show a distinct change related to the approaching of the end of life of the component. Possibly, a different and / or extended data analysis method, such as using multiple actuation frequencies rather than a single, or use a different method to calculate a value for the damage accumulation than just the maximum, may change this and provide some changing in the data that can be used as an indicator for approaching the
end of life. Alternatively, a threshold must be used. Such a threshold can be determined using for example ultrasound, yet is only applicable for similar structures, experiencing a similar loading and failure pattern. Differences in the loading and failure pattern may require a re-calibration of the threshold, which obviously is not practical and compromises the robustness of the method.

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