Acoustic Emission Damage Detection for Wind Turbine Rotor Blades Using Airborne Sound

THOMAS KRAUSE, STEPHAN PREIHS
and JÖRN OSTERMANN

ABSTRACT

Composite rotor blades of wind turbines are subjected to high dynamic load. This load can cause damages which can accumulate over time to critical structural damage. A system detecting defects early and reliably helps to react fast and to avoid critical damage. Such a method will enable the wind turbine operator to increase operational safety and minimize the economical burdens caused by downtime, maintenance as well as repairs and replacement.

One promising damage detection approach is acoustic emission event detection. In this regard acoustic emission events are stress waves emitted by a damage process. While other acoustic emission approaches use ultrasonic surface accelerations as input signals, we propose to use the airborne sound in audible frequencies and a sophisticated signal processing which can handle environmental noise.

We were able to perform a full scale rotor blade fatigue test until blade failure where one 44cm long continuous crack occurred. The test was continued and the crack was further increased. The evaluation of the airborne sound recordings shows that the continuous crack as well as parts of the crack propagation emitted cracking sounds. We modified our detection algorithm based on audio features in the time-frequency-power space by a power impulse feature. With this modification the algorithm detects the continuous crack as well as parts of the crack propagation without false alarms.

INTRODUCTION

When operating a wind turbine, damage of the rotor blade is a serious problem and has to be taken into account. Even relatively small damages of the blade can accumulate over time and lead to structural relevant damage. Therefore regular sight inspections are mandatory in many countries. Nevertheless these inspections cannot provide an instant damage detection. Besides the safety risk of an undetected damage, the economical burdens are increasing rapidly if the damage increases given the costs of repairs, replacement and downtime. A system detecting defects reliably and in early

T. Krause, S. Preihs and J. Ostermann, Leibniz Universität Hannover Institut für Informationsverarbeitung, Appelstr. 9A, 30167 Hannover, Germany

stages helps to react fast and to avoid greater damage. In modern wind turbines control units are implemented like the blade pitch control or an emergency shut-off system. These systems might also be triggered by a structural health monitoring system to avoid critical damage.

There is a whole variety of nondestructive testing methods and several approaches can be used for automatic damage detection of wind turbine rotor blades. An overview of the different methods can be found in [1][2]. For detecting damage automatically, reliably and in early stages many research projects focus on the acoustic emission event detection approach. The aim of this approach is to detect components of the stress wave caused by the damage process. For this, sensors mounted on the surface of the blade are used. With this approach small damages can be detected [1][2][3][4]. The sensors operate in ultrasonic frequencies, therefore the amount of sensors is relatively high due to the size of modern blades and high internal damping of composite materials in these frequencies [4][5]. This leads to at least about one sensor every one or two meter of the blade length which is quite a lot given the length of 50m to 70m of modern blades.

Using the acoustic emission approach for damage detection in an operating wind turbine is an unsolved problem. The higher risk of damage from lightning strikes caused by the electrical conductive wires is one of the main problems which prevents testing an acoustic emission approach in an operating rotor blade. So far there are only few results published using an acoustic emission system in a blade of an operating turbine [6][7][8]. Environmental noise during operation was observed which has to be taken into account to avoid false detections.

In contrast to other acoustic emission approaches, we propose to detect damages using airborne sound in the lower frequencies from about 200Hz to 20kHz by detecting cracking sound signals [9][10]. In these frequencies cracking sounds as well as environmental noise can be found. This issue can be solved by a sophisticated signal processing which can handle the noise. The benefit from using the airborne sound in these frequencies is a much smaller amount of sensors. We propose to monitor the whole rotor blade with only three microphones, which are mounted inside the blade. For this fiber optic microphones are used. Their cords are optical fibers which are non-metal, so they do not increase the risk of damage from lightning strikes. This makes the setup applicable in an operating rotor blade.

AIRBORNE SOUND DAMAGE DETECTION ALGORITHM

We presented a real time capable cracking sound detection algorithm in [9] and [10]. The algorithm uses audio features which represent characteristics of a cracking sound model. The cracking sound is described by an impulse with a low raising time over a wide frequency range. Its power is logarithmical decreasing towards high frequencies from the frequency with maximal power and also decreasing over time. The features of the algorithm are based on the power spectrum *P(k,l)* calculated by a windowed short-time Fourier transform *S(k,l)* by

$$S(k,l) = \sum_{n=0}^{n_{ft}-1} s\left(n + l \cdot n_{hop}\right) \cdot w(n) e^{-j\frac{2\pi nk}{n_{ft}}} \quad \text{where} \quad 0 \le k \le n_{ft} - 1 \tag{1}$$

$$P(k,l)=\left(n_{ft}\sum_{n=0}^{n_{ft}-1}|w(n)|^2\right)^{-1}|S(k,l)|^2 \quad \text{for} \quad k=0 \quad \text{and} \quad k=\frac{n_{ft}}{2} \tag{2}$$

$$P(k,l)=2\left(n_{ft}\sum_{n=0}^{n_{ft}-1}|w(n)|^2\right)^{-1}|S(k,l)|^2 \quad \text{for} \quad 0<k<\frac{n_{ft}}{2}\,. \tag{3}$$

Where s is the input signal, w is the window function, n_{ft} the Fourier transform length and n_{hop} the overlapping of the windows. Here k is the frequency index and l the time index.

A feature f_I was added to the detection algorithm which measures the impulse-like power of the sound in dB and is calculated by

$$f_I(l)=10\log_{10}\left(\sum_{k=k_s}^{k_e}\sum_{l}^{l+\Delta l}P(k,l)\right). \tag{4}$$

With this feature we intend to get an indicator which reflects the relevance of a signal. Our assumption is that cracking sounds with high power are only emitted by structural relevant damages. The bandwidth from which the power is calculated is set with the parameters k_s and k_e. Here the power below 562.5Hz was not used due to high noise during the blade test in these frequencies. With Δl the time span can be adjusted. Here it is set to a value which represents a time period of 53.3ms. This covers the first part of an impulse.

The damage detection algorithm uses five other features which are listed as follows and were described in detail in [10]:

- Power gradient feature: measures if the signal is impulse-like in a wide frequencies range,
- Spectral flatness feature: measures if the signal is tonal or noise-like,
- Spectral slope feature: indicates a decrease in power towards high frequencies,
- Spectral similarity feature: calculates the euclidean distance to a linear model curve,
- Power slope feature: tests if the impulse power is decreasing.

All features are compared to threshold parameters to see if the signal is similar to a cracking sound. The principle flow chart of the algorithm is displayed in Figure 1.

ROTOR BLADE FATIGUE TEST

A test campaign with a 34m long blade was performed. The campaign included an edgewise fatigue test until failure of the blade. With this, the longtime stress behavior

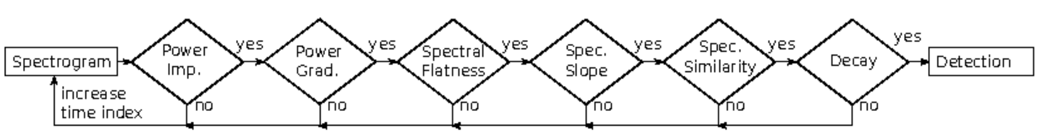

Figure 1. Principle flow-chart of the cracking sound detection algorithm.

of the blade is tested in a relatively short time. The test procedure is similar to the part of a rotor blade certification test described in [11]. One difference is the load which was increased step by step to provoke damage of the blade. The other difference is that at least one full visual inspection was done every day. The coating of the blade at the trailing edge was removed before the test which provided better inspection possibilities of this area.

To monitor the blade and for gaining additional measurement data, strain gauges, accelerometers in different frequency domains and velocity sensors were used as well as three fiber optical microphones which were installed inside the blade according to Figure 2. During the test the audio data was recorded non-stop with 96kHz sampling rate and 24bit precision.

The general problem of all full-scale rotor blade tests is finding all damages that occur within each test period since the reference method is a visual inspection which has limitations in reliability and accuracy. Especially small damages can easily been overseen or occur in parts which can not be inspected. In our case the coating additionally prevented an accurate outside inspection of other parts than the trailing edge. Therefore, for the inspection we also used thermal cameras, which gave us hints of damage locations.

EVALUATION OF THE ROTOR BLADE FATIGUE TEST

In Table I a summary of the fatigue test and all documented damages is shown. Here 100% load is the calculated load at which the blade should collapse given the number of one million cycles. The time line is from bottom to top.

During the first part of the rotor blade test only a lot of very small damages occurred. These small damages were glue cracks of overflowed glue at the trailing edge, small delaminations, small cracks of the blade coating, small inner cracks and small surface cracks of the first layers where in few parts small pieces of the matrix of the outer layers were detached. All in all 213 small damages were found. This number includes increasing of small damage. We assume that none of these damages was relevant for the integrity of the structure since the sizes were small and the other characteristics of the damages also indicate a low significance, e.g. the amount of layers were a crack was present. A structural relevant damage occurred at the second run with 170% load. The damage can be assigned to a narrow time span. A loud cracking sound occurred during the test as well as a sudden decrease at some of the strain gauges and the test was stopped immediately. There are two possible scenarios for what happened. First, the whole damage occurred during this event or second, a

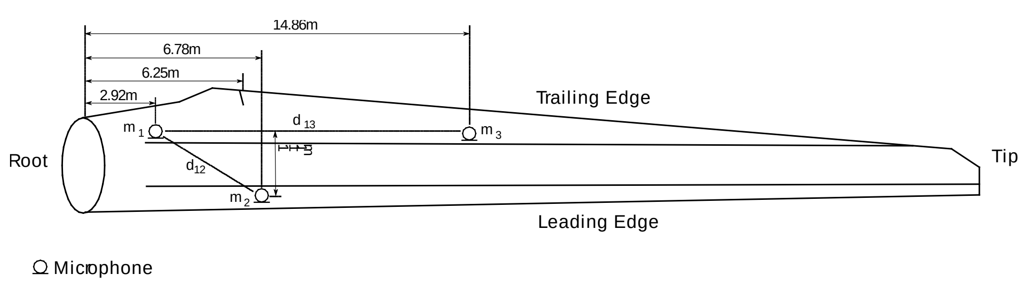

Figure 2. Principle drawing of the rotor blade and microphone positions.

damage which occurred earlier in the same test run was greatly increased within this event. The continuous crack cut all layers of the trailing edge and affected therefore the suction and pressure side. The crack length was at the beginning about 44cm on both sides. There was a crack side arm on the pressure side which did not affect all layers and had a length of about 7cm. The crack was located at the length of about 6.25m measured from the root of the blade.

The test was continued with lower load to increase the crack. At the end of the fatigue test the length of crack propagation in total was about 29.1cm (adding the crack propagation of the three crack arms). In total 1.25 million load cycles were performed.

EVALUATION OF THE MICROPHONE SIGNALS

All cracking sounds in the three microphone signals were manually labeled. The time of occurrence was labeled and events were marked when a sound was found in more than one microphone signal. With the assumption that relevant damages emit high power sounds, this information is important for detecting these damages. The power of one microphone signal is not sufficient for this since a sound source with low power which is close to one microphone also generates a signal with high power.

There were a lot of cracking sounds which have low power and which can not be found in all microphone signals. These sounds were only recorded by the two microphones facing the trailing edge and are listed in Table I in the column SE_l.

We tried to match the quiet cracking sounds with the results of the visual inspection but we did not find a valid relation between damages or damage types and the low power sound signals. In a few time slots small damages occurred near one microphone and cracking sounds with lower power were found. But there were also cases where small damage near one microphone occurred and there is no cracking sound in the microphone data in this time slot.

There are seven sound events which have high power and which are present in all microphone signals. These sounds are listed in Table I in column SE_h. There are two sounds in test number 28 before the relevant damage. The cause of these events may be a damage in an early stage. Two consecutive cracking sounds which have the highest power of all cracking sounds can be associated with the occurrence of the continuous crack. The sounds in test number 36 and 38 are with high probability caused by crack propagation, since there were no other damages found in these time slots. In Table II all cracking sounds with high power are listed. Here f_{Ij} is the power of the first part of the impulse which is the output of the power impulse feature of the signal from microphone j.

The results from the evaluation of the visual inspection and the airborne sound data support the assumption that the power of cracking sound signals can be used as an indicator for the relevance of a damage. The signals with high power only occurred in test slots where relevant damage happened. In addition the differences in the three microphone signals in signal power, high frequency content and time of arrival support the thesis that the source of all high power signals is the location of the continuous crack. So the airborne sound signals can here be used for rotor blade damage detection by finding high power cracking sounds.

TABLE I. OVERVIEW OF THE FATIGUE TEST. HERE SE IS THE NUMBER OF CRACKING SOUND EVENTS, SE_l INDECATES LOW POWER EVENTS AND SE_h ARE HIGH POWER EVENTS.

Test #	Cycles	Load [%]	Damages	SE_l	SE_h
38	5.285	130	Crack propagation by 17.7cm	14	2
37	5.002	115	Crack propagation by 2.2cm	0	0
34 - 36	13.094	105	Crack propagation by 8.9cm	3	1
29 - 33	14.063	50, 70, 90	Crack propagation by 0.3cm	1	0
28	4.198	170	Continuous crack	84	4
27	2.048	170	6 small damages	16	0
26 - 24	85.437	140, 130	36 small damages	3	0
23 - 21	72.069	120	36 small damages	4	0
1 - 20	1.051.836	70 - 120	135 small damages	3	0

TABLE II. LIST OF ALL CRACKING SOUNDS WITH HIGH POWER IN THE THREE MICROPHONE SIGNALS

Signal #	Test #	Cause of the sound	f_{I1} [dB]	f_{I2} [dB]	f_{I3} [dB]
7	38	Crack propagation (p)	-73.7	-76.8	-73.5
6	38	Crack propagation (p)	-71.6	-80.3	-76.2
5	36	Crack propagation (p)	-67.1	-74.1	-70.3
4	**28**	**Continuous crack (c)**	**-48.8**	**-60.3**	**-55.8**
3	**28**	**Continuous crack (c)**	**-42.9**	**-54.1**	**-51.4**
2	28	Most likely damage which led to the continuous crack (b)	-65.9	-78.1	-73.6
1	28	Most likely damage which led to the continuous crack (b)	-62.4	-72.5	-61.9

RESULTS OF THE DETECTION ALGORITHM

According to the evaluation of the sound signals and the visual inspection we intended to detect all cracking sounds with high power. The results using the previous version of our detection algorithm were not sufficient for this case. Here the majority of the detected sounds were cracking sounds with low power and only two high power cracking sounds were detected in the signal of microphone one and none in signal two and three. With the introduced power impulse feature the threshold values of the detection algorithm could be further optimized. The goal here was to find a parameter set which can be used for all microphone signals. With this strategy we try to find a parameter set for the algorithm which is more general and is not prone to position changes.

The results of the detection algorithm for processing the whole fatigue test recordings are shown in Table III. Here the influence of the threshold parameter of the power impulse feature δf_I, in the region where the first false positive detections occur, is displayed. TP is the true positive rate, c stands for the events where the continuous crack occurred, p indicates the sounds of the crack propagation and b stands for the events before the continuous crack. FP is the number of false positive detections. The threshold parameter can be set that no false Positive detections were made. For lower δf_I almost all false detections were made in test number 27 and 28 were the noise level of the test is significantly higher compared to the other time slots, given the very high load of the blade. This shows the limitations of the algorithm. If noise with very high power and similar impulse characteristic occurs it is still possible to detect cracking sounds which were emitted by the crack propagation without false alarms but not in every microphone position. The results for detecting the two occurrences of the continuous crack are significantly better. These events were detected by processing any of the three microphone signals on its own and this can be done without getting any false alarms.

CONCLUSION

In this paper it is shown that airborne sound signals are suitable for detection of rotor blade damage. The approach presented uses acoustic events which are emitted by the damage process. A full scale rotor blade fatigue test till blade failure was performed. During the test one structural relevant 44cm long continuous crack occurred. The blade test was continued with lower load and the continuous crack was increased step by step. The airborne sound was recorded inside the rotor bade using three fiber optical microphones. The evaluation of the audio signals and the matching with the results of the visual inspection show that the continuous crack as well as parts of the crack propagation emitted sounds with high power which can be found in all microphone signals.

TABLE III. RESULTS OF THE DETECTION ALGORITHM FOR DIFFERENT SETTINGS OF THE THRESHOLD PARAMETER δf_I. TP IS THE TRUE POSITIVE RATE, FP IS THE NUMBER OF FALSE POSITIVE DETECTIONS.

	Microphone 1				Microphone 2				Microphone 3			
δf_I	TP_c	TP_p	TP_b	FP	TP_c	TP_p	TP_b	FP	TP_c	TP_p	TP_b	FP
-70	2/2	1/3	2/2	0	2/2	0/3	0/2	0	2/2	0/3	1/2	0
-71	2/2	1/3	2/2	0	2/2	0/3	0/2	0	2/2	1/3	1/2	0
-72	2/2	2/3	2/2	0	2/2	0/3	0/2	0	2/2	1/3	1/2	0
-73	2/2	2/3	2/2	1	2/2	0/3	1/2	3	2/2	1/3	1/2	0
-74	2/2	3/3	2/2	144	2/2	0/3	1/2	11	2/2	2/3	1/2	6
-75	2/2	3/3	2/2	3711	2/2	0/3	1/2	17	2/2	2/3	1/2	18
-76	2/2	3/3	2/2	11898	2/2	0/3	1/2	30	2/2	2/3	1/2	15

A real-time capable damage detection algorithm is presented which detects these cracking sounds and can handle environmental noise. The algorithm uses audio features in the frequency-time-power space. In this work a feature was added which measures the impulse power. This feature is used as an indicator for the relevance of the signal. Parts of the few cm crack propagation are detected in the signals of two of the three microphones with no false alarms. The algorithm detects the 44cm continuous crack in all three microphone signals with no false alarms.

There is still research needed to determine the capabilities and limitations of this new approach more detailed. Nonetheless the presented results, which were achieved by processing only three microphone signals for monitoring the whole blade, are very promising. Since the results were obtained with fiber optical microphones, which do not increase the risk of lightning strike damage, the approach is highly useable in an operating wind turbine.

ACKNOWLEDGEMENTS

This research was founded by the German Federal Ministry for Economic Affairs and Energy.

REFERENCES

1. C. C. Ciang, J.-R. Lee, and H.-J. Bang. 2008. “Structural health monitoring for a wind turbine system: a review of damage detection methods” Measurement Science and Technology 19, page 20 ff
2. J. Schubel, R.J. Crossley, E.K.G. Boateng, and et al. 2012. “Review of structural health and cure monitoring techniques for large wind turbine blades” Renewable Energy, 51:113-123
3. G. R. Kirikeraa, V. Shindea, M. J. Schulza, and et al. 2007. “Damage localisation in composite and metallic structures using a structural neural system and simulated acoustic emissions.” Mechanical Systems and Signal Processing, 21:280–297
4. A.G. Beattie. 1997. “Acoustic Emission Monitoring of a Wind Turbine Blade During a Fatigue Test” In 35th Aerospace Sciences Meeting
5. P. A. Joosse, M. J. Blanch, A. G. Dutton, and et al. 2002. “Acoustic Emission Monitoring of Small Wind Turbine Blades. Journal of solar energy engineering” 124(4):446–454
6. D. Papasalouros, n. Tsopelas, I. Ladis et al. 2012. “Health Monitoring of a NEG-MICRON NM48/750 Wind Turbine Blade with Acoustic Emission” 7Th International Conference on Acoustic Emission
7. M.J. Blanch and A.G. Dutton. 2003. “Acoustic Emission Monitoring of Field Tests of an operating Wind Turbine” Key Engineering Materials Vols. 245-246, pages 475–482
8. O. Ley and V.F. Godinez-Azcuaga. 2013. “A wireless system for structural health monitoring of wind turbine blades” Safety, Reliability, Risk and Life-Cycle Performance of Structures and Infrastructures, pages 275–279
9. T. Krause, S. Preihs and J. Ostermann. 2014 “Detection of Impulse-Like Airborne Sound for Damage Identification in Wind Turbine Rotor Blades” EWSHM
10. T. Krause, S. Preihs and J. Ostermann. 2014. “Airborne Sound Based Damage Detection for Wind Turbine Rotor Blades Using Impulse Detection in Frequency Bands” 1st International Wind Engineering Conference
11. IEC 61400-23 TS Ed.1. 2001. “Wind turbine generator systems – Part 23: full-scale structural testing of rotor blades”