Acoustic Emission Localization Using Airborne Sound: Where Did the Wind Turbine Rotor Blade Crack?

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Abstract

When operating a wind turbine, damage of rotor blades is a serious problem which has to be taken into account. The position of the damage is an important information which is connected with the damage significance. Therefore a monitoring system which estimates the position helps to make better decisions for maintenance and repairing. One promising approach for detection and localization of damages in early stages are acoustic emission (AE) methods which detect and localize damage events. In contrast to most AE approaches which require about 12 to 40 sensors, we propose to use the airborne sound in lower frequencies up to about 30 kHz with only three fiber optical microphones. Based on this approach a damage localization algorithm was developed which uses time differences of arrival (TDOA) of the damage signals from microphones which are placed at different positions inside the blade. The localization algorithm estimates in which part of the blade the damage occurred and the distance to the root of the blade. The localization results of seven damage events, which happened during a fatigue test of a 34m rotor blade are presented. An average distance error of about 1.4m for the damage event localization was achieved.

1. Introduction

Increasing the efficiency and safety of wind turbines is one important design goal which leads to many different research activities. Unexpected rotor blade damage is here one important problem. In [1] the relevance of rotor blade damage for operating a wind turbine is shown. Regular sight inspections of the blades are therefore mandatory. Nevertheless these inspections cannot provide an instant damage detection and classification and the rotor blades operate in an unknown health state for long time periods. Besides the safety risk of a damage, the economical burdens are increasing rapidly if the damage increases, given the costs of repairs, replacement and downtime.

Monitoring the rotor blades is an approach to ease the problem. A system which detects reliably rotor blade damages and ideally provides all relevant information of the damage gives much better scope for action so that an optimal decision how to handle the situation can be made. One very important information is the position of the damage which helps to estimate the severity of a damage and is therefore a key element for further calculations and decision making.

One promising approach for damage localization is based on acoustic emission event detection commonly referred to as acoustic emission (AE) [2]. A damage event causes sound waves which are emitted in the structure and directly or indirectly in the air. Common AE methods use the structural sound wave which are detected by monitoring physical values like the acceleration of the surface of the material. With the use of multiple sensors the waves can be used to localize the damage using passive sonar techniques like time difference of arrival (TDOA) localization. Here the signals are captured at known sensor positions. The TDOAs of signal pairs are used to localize its source. Damage localization approaches using AE with structural sound signals require a known radiation pattern of the source and a known group velocity of the wave and damage signals which are strong enough to be detected at least at one sensor. Looking at the sound propagation in the complex rotor blade structure some requirements can only be roughly fulfilled therefore the localization is usually done using plenty sensors [3][4].

In contrast to other AE approaches, we propose to detect the AE using airborne sound in lower frequencies from from about 500Hz to 35kHz by detecting cracking sound signals [5]. The aim is to lower the amount of sensors and to use fibre optical microphones, which do not increase the risk of lightning strike damage. The downside of this technique is higher noise events at these frequencies and the ability to only detect significant damages. We present in the following a damage localization approach which is described in section 2. A fatigue rotor blade test of a 34m rotor blade is described in section 3. Then the results of the localization algorithm are presented. The last section concludes the research.

2. Damage Localization Algorithm

The localization using time differences of arrival (TDOA) can be divided into two parts. The first part is to estimate the TDOAs using two microphone signals. The second step is to state an equation system with the estimated TDOAs and to find the position by solving the equation system. In the following two sections the rotor blade localization algorithm consisting of these two steps is presented. The localization algorithm gets damage event signals as input which are about half a second long and contain the start of the damage sound at an unspecified time point.

2.1 TDOA Estimation

2.2.1 Cross correlation TDOA estimation

A popular method to estimate TDOAs is by using weighted cross correlation functions. The assumption is that the signals of tow microphones are similar in the time domain and therefore the maximum of the cross correlation function indicates the TDOA. Different weighting functions were introduced which can provide better performance [6]. The cross correlation is stated as follows

$$\Delta t_{12} = \frac{1}{f_s} \underset{n}{\operatorname{argmax}} \frac{1}{2\pi} \int_{-\infty}^{+\infty} \phi(\omega) X_1(\omega)\, X_2^*(\omega)\, e^{j\omega n} d\omega. \quad (1)$$

Here is $\phi(\omega)$ a frequency dependant weighting function, X_1 the frequency representation of the time amplitude signals x_1 and * denotes the complex conjugate. There are different weighting functions with

$$\phi_c(f) = 1 \text{ and } \phi_p(\omega) = \frac{1}{\left|X_1(\omega)X_2^*(\omega)\right|} \,. \qquad (2)$$

In this paper the classical cross correlation (CCC) ϕ_c was used, which represents a baseline method. As a second method the phase coherent cross correlation (PHAT) ϕ_p was tested, which has shown good results in a variety of scenarios [7].

2.2.2 Impulse response based TDOA estimation

The least mean square (LMS) algorithm and adaptive eigenvalue decomposition (AED) algorithms both estimate impulse response(s) from which the TDOA can be estimated [8]. The assumption of the LMS algorithm is that the measured signals *x(n)* of both microphones are connected as follows

$$x_2(n) = h(n) * x_1(n). \qquad (3)$$

The impulse response *h* is estimated by using the least mean square optimization.

In a similar way two impulse responses were estimated with the AED algorithm. Here the measured signals *x* are connected as follows with the source signal *s*

$$x_1 * h_1 = x_2 * h_2 = h_1 * h_2 * s. \qquad (4)$$

The impulse responses h were derived by estimating the eigenvector of the eigenvalue 0 of the covariance matrix. In the final step the TDOA Δt_{nm} is calculated by

$$\Delta t_{12} = \left(argmax_n \left|h_1(n)\right| - argmax_n \left|h_2(n)\right|\right)/f_s \qquad (5)$$

where f_s is the sample frequency. Details of these algorithms can be found in [8].

2.2.3 Spectral centroid TDOA estimation (SPEC)

In the following a new TDOA estimation algorithm is presented which was designed using the findings of an airborne sound damage detection algorithm given the special conditions for damage sounds in rotor blades. In a first step the audio data is transformed into a spectrogram representation. For this the discrete time amplitude signal *x(n)* is transformed by a discrete short time Fourier transform with overlapping windowed time chunks by

$$S(k,l) = \sum_{n=0}^{N-1} x\left(n + l\frac{N}{2}\right) w(n) e^{-j\frac{2\pi nk}{N}} \qquad (6)$$

Here is l the resulting time and k the frequency index in the interval of $0 \leq k/N - 1$. A hamming window *w(n)* is used with the same length as the transformation length N

which correspond in this application to 0.33ms. Here half overlapping time chunks are used. The power spectrogram *P(k,l)* is calculated using the squared absolute value and a normalization according to

$$P(k,l) = 10\log_{10}\left(\frac{a}{N\sum_{n=0}^{N-1}|w(n)|}|S(k,l)|^2\right). \quad (7)$$

In the case of $k = 0$ or $k = N/2$ the parameter a equals 1 in all other cases a is 2. In the following step the spectrogram data is high pass filtered by simply using frequencies greater than 7.96kHz.

The TDOA estimation algorithm is based on the spectral centroid feature which calculates as followed

$$s(l) = \frac{\sum_{k=k_s}^{k_e} F(k)P(k,l)}{P(k,l)}, \quad (8)$$

where F is a vector containing the center frequencies of all frequency bins. The spectral centroid represents the frequency were the centre of power is present. In a next step the signals is smoothed by using an average operator over a time frame which correspond to 6.7ms. As a starting point the time bin where the minimal spectral centroid occurs is used. From this point the time bin l_d where the spectral centroid is lower than the threshold d is found by backwards checking every spectral centroid value. With this the time point were the spectral centroid is first time significantly decreased is found. This is the assumed time of arrival. The procedure is done with two microphone signals and the time difference Δt is calculated by

$$\Delta t_{12} = \frac{N}{2f_s}\cdot(l_{d1} - l_{d2}). \quad (9)$$

2.2 TDOA Localization

With the calculated TDOAs Δt_{12} the position of the damage is estimated. A two dimensional representation of the three dimensional problem is used. The assumptions for solving the TDOA problem are known sensor positions, a constant known speed of sound c and a spherical wave emitted by the source. The TDOA equation for localization can be stated by

$$c_{air}\cdot\Delta t_{12} = \|V_s - V_2\| - \|V_s - V_1\|. \quad (10)$$

Here is V the position of the microphone *1* and *2* as a vector and V_S the position of the source. In a 2D scenario the resulting TDOA function is a hyperbola. With the use of the rotor blade geometry, side conditions can be used to estimate the damage position alongside the rotor blade. For this the rotor blade is modelled in a 2D rectangular form which provides linear equations. These are used to calculate the intersection with the hyperbola. In the following the damage localization algorithm is explained for the configuration which is shown in Figure 1. The steps can be adapted to different microphone rotor blade configurations. In Figure 1 a model of the geometry of our 34m rotor blade with the positions of the microphone is shown. This set-up was tested in a rotor blade fatigue test which is described in Section 3. This set-up was intended to find the damage position of the trailing edge.

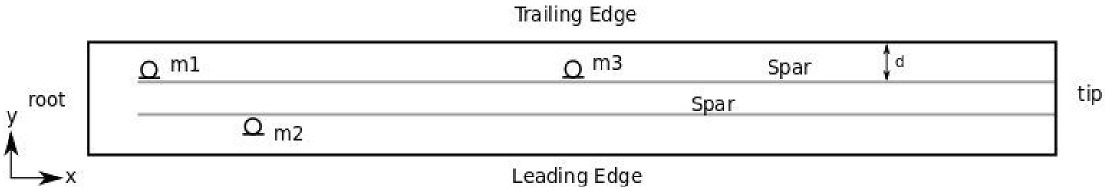

Figure 1. Principle drawing of the rectangular representation of the rotor blade

Wind turbine rotor blades have chambers inside the blade which are formed by one or more spars. In this case there are three long chambers one at the trailing edge, the leading edge and one in the middle between the two spars. In this scenario damage was expected at the trailing edge therefore two microphones were mounted in the trailing edge chamber. The distances *d* between the spar and the trailing edge lines are approximated by the edge component to the spar. To calculate the position of the damage in the x-component is the aim of the algorithm. This is achieved by choosing automatic the two microphones which have the shortest line of sight (LOS) path in the air to the damage position. This is done by calculating for an event the difference between the maximum and the mean spectral centroid value. A high value indicates an event which is LOS and close to the microphone position. Two microphone signals which provide the highest values are then chosen and the TDOA is calculated using on of the methods described in Section 2.1.
Here m1 and m3 should be found since in this scenario the damage in the trailing edge chamber should be localized. The damage position is calculated by finding the intersection of the line segment of the trailing edge or the root or tip line with the hyperbola derived by the TDOA13.

3. Rotor blade data

An edgewise fatigue test with a 34m rotor blade was performed. The test aims to simulate the long-time stress of the blade in a relatively short time period. Here the blade is mounted with the root in a test block and force is induced over one load frame which is mounted at the blade. The blade is excited near its first eigenfrequency so that the stress is distributed over the whole blade. The procedure is similar to the fatigue test for blade certification which is described in detail in [9]. 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.
For our method three fibre optical microphones were installed inside the blade according to Figure 2. The microphones were mounted on the spars of the blade facing towards the trailing and leading edge, respectively. Damping spiders were used for lowering the influence of vibrations induced into the microphone. The directionality of all microphones is specified as omnidirectional. During the test the audio data was recorded non-stop with 96kHz sampling rate and 24bit precision.

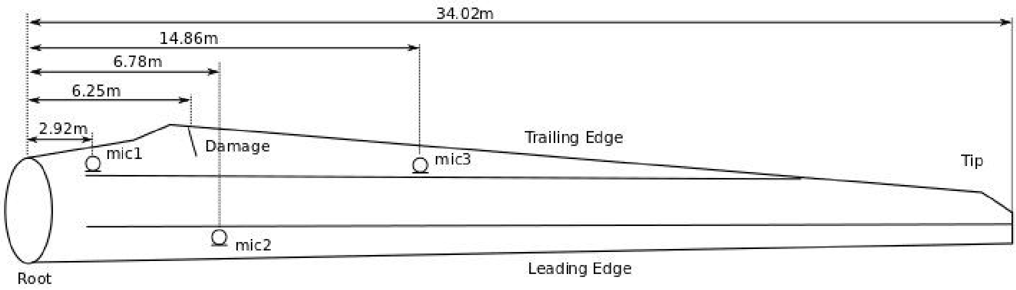

Figure 2. Principle drawing of the rotor blade measurements set-up of the fatigue test. At 6.25m the trailing edge crack occurred.

A structural relevant damage occurred at the second run at 170% load. The damage can be assigned to a narrow time span. Two consecutive 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. The continuous crack was present in 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. There is a margin of tolerance of the exact position since the curvy geometry of the rotor blade prevents to easily measure the component in one dimension.

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). 1.25 million load cycles were performed during the whole fatigue test.

There are seven sound events which have high power and which are present in all microphone signals. The amount of background noise differs according to the load. These sounds are listed in Table 1. There are two sounds in the second run at 170% load before the relevant damage occurred. The cause of these events is an early damage stage of the continuous crack of the trailing edge. Two consecutive cracking sounds which have the highest power of all damage sounds can be associated with the occurrence of the continuous crack. The sounds which occur after 170% load are caused by crack propagation.

Table 1. Overview of the fatigue test

Load [%]	Cycles [k]	Visual inspection	AE h
70-170	902	Insignificant damages, higher noise level	0
170	3	Damage 44cm, higher noise level	4
50-90	10	Crack propagation 0.3cm, lower noise level	0
105	10	Crack propagation 8.9cm, lower noise level	1
115	4	Crack propagation 2.2cm, lower noise level	0
130	4	Crack propagation 17.7cm, lower noise level	2

4. Results

First the theoretical limitations of the localization algorithm are investigated. Given the limitations of the TDOA localization it is not possible to differentiate any position which is not between to sensors given only one TDOA. In between the sensors the minimal position change which can be detected is bounded by the following equation

$$x_m = c\frac{N}{2f_s}\,. \qquad (11)$$

With c, N and f_s as given before. In this case the highest theoretical resolution which might be obtained is 5.7cm for the SPEC algorithm and a few millimetres using all other TDOA methods presented in Section 2.1. The distance d which defines the line of the trailing edge in the model as well as the 2D approximation has only a minor influence on the accuracy if the damage position is slightly of the middle between the sensors at 8.9m length. For one meter derivation in hight or depth the calculated length position shifts about 5.5cm. The same derivation of one meter in hight or depth given the damage position at 13.66m lenght (90% the distance between the microphones) shifts the calculated length position significantly more with about 38cm.

The damage localization algorithm described in Section 2 was tested using the measurements of the fatigue test (Section 3). In Table 2 the results using the five TDOA estimation methods from Section 2 are shown. As a preprocessing step a linear phase high pass filter was used with a cut off frequency of 7.96kHz. This shows much better results since the signal to noise ratio was higher in these frequencies. Additionally the influence of the overlaid structure sound signal path which constantly emits airborne sound should be lower, because of the higher damping of the composite fibre in these frequencies. The localisation algorithm identifies for all events TDOA13 as the best TDOA. With the new SPEC TDOA estimation the algorithm provides a decent localisation accuracy of all seven damage events.

Table 2. Results of the localization algorithm using all damage event from the fatigue test of the 34m rotor blade. TDOA 13 was used by the algorithm

TDOA Method	Mean Error [m]	Max absolute error [m]
CCC	4.12	7.78
PHAT	3.30	7.78
AED	3.92	5.34
LMS	3.92	5.34
SPEC	**1.35**	**2.12**

5. Conclusion

In this paper a localization algorithm that uses airborne sound acoustic emission signals to estimate the damage position in a wind turbine rotor blade was presented. A new method to estimate the time difference of arrival was used to achieve the about three times smaller average localisation error compared with four established TDOA estimation methods. Seven damage events which occur during a fatigue test of a 34m rotor blade were localized by the algorithm with a mean error of 1.35m and and a maximum absolute error of 2.12m.

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