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Damage Detection in Wind Turbine Blades using two Different Acoustic Techniques

ANNE JÜNGERT

Materialprüfungsanstalt Stuttgart, University of Stuttgart
Pfaffenwaldring 4, D-70550 Stuttgart, Germany
anne.juengert@mpa.uni-stuttgart.de

Abstract

Facing the climate change the use of renewable energies gains in importance. Especially the wind energy branch grows very fast. Bigger and more powerful wind mills will be built in the next decades and the safety of the mills will play a major role. Wind turbines are treated as buildings and therefore have to be inspected at regular intervals. Especially the turbine blades are highly stressed during operation and a blade breakdown can cause a big economic damage.

The turbine blades consist of glass fiber reinforced plastics (GFRP) and sandwich areas containing wood or plastic foam. The blades are manufactured as two halves and glued together afterwards. Typical damages are delaminations within the GFRP or the sandwich and missing adhesive or deficient bond at the bonding surfaces.

The regular inspections of wind turbine blades are done manually by experts and are limited to visual appraisals and simple tapping tests. To improve the safety of wind turbine blades non-destructive testing techniques using acoustic waves are being developed.

To detect delaminations within the laminates of the turbine blade a local resonance spectroscopy is used. A small hammer is used to tap onto the blade and the excited sound is recorded using a microphone. A structural change within the material is displayed in a change of the frequency content. Furthermore the exciting signal is recorded and gives additional information about the structural health of the wind turbine blade.

To detect missing or kissing bond areas from the outside of the blade the impulse-echo-technique is used. An ultrasonic pulse is sent into the material and is reflected at flaws or material boundaries. This pulse has to be strong because the GFRP are highly damping. It is difficult to see through several centimeters of GFRP and the choice of the ideal transducer is very important. To inspect bonding areas from outside the blade will be a great advance in wind turbine safety.

1. Introduction

In January 2008 the Commission of European Communities declared the reduction of 20 % in greenhouse gases and a growth in renewable energies from current 6.6 % to 20 % in the EU overall energy consumption until 2020. Additionally the electricity production is treated individually in the *Directive on the Promotion of Electricity Produced from Renewable Energy Sources in the Internal* [1] announced by the European Parliament in 2001. According to this directive 21% of the electricity shall be gained from renewables until 2010. The target value for Germany was scheduled to 12.5 % in the Renewable Energies Act (EEG, [2]) and was already achieved in 2007. Recently it has been elevated to a 25 to 30 % share until 2020.

Germany takes a leadership role in the investigations in wind energy. More than 40 % of its electricity from renewable energy sources is generated using wind power. At present there are more than 18,000 wind plants running in Germany producing more than 20,000 MW power. Both the highest and the most powerful wind energy plants are running in Germany.

To increase the use of renewable power sources more and more powerful wind energy plants will be built in the next decades. Additionally older plants will be repowered and new areas will be opened up to the wind power use. It is inescapable that in the future people will live nearer to wind turbines. Therefore the safety of the plants will come to the fore to avoid accidents. If the electricity market depends more on wind energy, it will be necessary to keep downtimes of wind energy plants short to guarantee the electricity supply.

The use of non-destructive testing techniques will improve the regular inspections of wind turbine blades. During a so-called InnoNet-Project by the project executing organization VDI/VDE, funded by the German Ministry for Economy and Technology, a combination of techniques using acoustic and electromagnetic waves, will be developed for practical application. The acoustic techniques will be presented in this paper and are developed to work simultaneously to the electromagnetic techniques.

2. Wind turbine blades and damage symptoms

In Germany wind energy plants are treated as buildings and the structural safety has to be evaluated at regular intervals. Besides the tower and the gear, the turbine blades are, due to the constant wind contact, highly stressed parts and have to be inspected regularly by experts. However, the current inspection techniques are only very rough and limited to visual inspections and manual tapping tests. Both techniques require a highly experienced expert and are not able to detect internal damages at an early stage. Figure 1 shows an industrial climber roping from the rotor of a wind turbine to inspect critical areas of the blades. Besides the use of basket cranes this is a common way to get access to the blades.

Figure 1: Inspection of a wind turbine blade. The inspector ropes from the rotor and inspects the leading and the trailing edge.

Modern wind turbine blades mainly are built from fiber reinforced plastics combined with lightweight materials like wood or plastic foam. Because of the lower price, glass fiber reinforced plastics (GFRP) are preferred to carbon fiber reinforced plastics (CFRP). The blades have an aerodynamic shape and use buoyancy to convert the energy carried by the wind into rotational energy which is then transformed into electric energy by a generator.

The turbine blades are manufactured as to halves which are laminated separately and glued together afterwards. The blade is protected from ultraviolet degradation and water penetration by a gelcoat, which is made from epoxy or polyester thickened with silicic acid. In the manufacturing process the gelcoat is brought in the lamination shapes first. The fiber-laminates are put in afterwards and the resin is drawn in using vacuum injection. After lamination of both halves the adhesive is inserted and the bars are placed before the halves are combined.

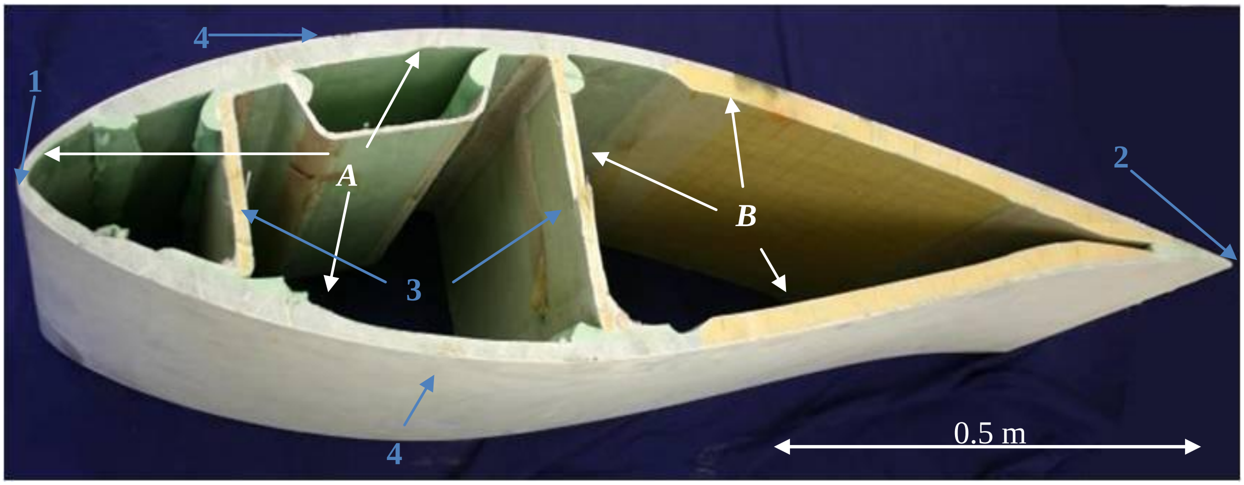

Figure 2: Cross section of a wind turbine blade. The upper side in the picture is called intake side the lower side is called pressure face. On the left the leading edge (1) and the trailing edge (2) can be seen. The bars (3) stabilize the turbine blade and are glued to the belts (4). Large areas are built of GFRP (A). To reduce weight some regions (B) are built as composite of GFRP and wood or plastic foam.

A typical cross section of a wind turbine blade is shown in Figure 2. The main structural parts can be identified. Due to the aerodynamic profile the upper side of the turbine blade is the intake side and the underside is called pressure face. The so-called belts (4) are built from GFRP (or sometimes CFRB) and carry the two bars (3) which stabilize the blade. The bars are manufactured as sandwich from plastic foam or balsa wood covered with a thin layer of GFRP. Other parts of the blade, which form the aerodynamic shape, as well are built in sandwich construction. The leading and the trailing edge are completely built from GFRP. The bonding areas are located at the leading edge, the trailing edge and at the contact areas of the bars with the belt.

2.1 Damages in wind turbine blades

Damages in sandwich areas wind turbine blades are various and various in importance. One can discriminate symptoms of fatigue from manufacturing errors.

Symptoms of fatigue

The leading edge has to stand the wind forces and by-and-by the gelcoat is eroded and water and UV-radiation is able to infiltrate and weaken the GFRP. The trailing edge is just several millimeters thick and highly stressed by stall. Delaminations of the trailing edge are common and until now can't be detected before they are visible at the blades surface. Other damages due to fatigue are for example delaminations within the GFRP-laminates, stress whitening or debonding of matrix and fibers. Erosion of the leading edge is decelerated by protection films that are sticked onto the gelcoat. The load on the trailing edge is reduced using diverse vortex generators to cause an earlier stall.

Condition Monitoring Systems (CMS) are now being established in new turbine blades using embedded or fiber sensors ([5], [8]). Failure of fibers and changes in the natural oscillation are recorded and damages can be detected at an early stage. Not all manufacturers use those CMS and there is a big amount of wind turbine blades, which have to be inspected conventionally.

Manufacturing errors

Manufacturing errors can't be detected by CMS as they are in the blade from the outset. The manufacturing process of wind turbine blades is nowadays highly automated and many problems have already been eliminated. But there are still critical areas which are not accessible with common inspection techniques.

During the lamination process it can happen that air is trapped within the laminates or some parts of the laminates are not immersed with resin. These areas are mainly not visible during and after the manufacturing process but of course affect the rigidity of the turbine blade.

Other critical regions are all bonding areas. The bonding has to be done without a visual control. Some manufacturers use infrared cameras to visualize the adhesive during hardening. Areas with too little or too much adhesive can be detected. However, this technique is not applied to all operating blades and furthermore is not possible to give evidence about the quality of the bond. Too little adhesive leads to missing bond between the two halves. Too much adhesive brings in additionally weight and can cause unbalanced masses. Furthermore the presence of too much adhesive affects the hardening process and can lead to fissures within the bond. Even if the amount of adhesive is correct, it is possible that no bonding is coming about, the so-called kissing-bond. Especially the bonding areas are of high interest during an inspection, but can't be inspected from the outside of the blade until now. To access the interior of the turbine blade is only possible in the first third of the blade, where it is at least 60 centimeters thick.

3. Non-Destructive Testing (NDT) techniques

3.1 NDT at fiber reinforced plastic

Non destructive Testing (NDT) techniques are already used to detect damages inside reinforced plastics for years in aerospace industries. The durability of reinforced plastics heavily depends on the compound of matrix and fibers. In space even small particles are strongly accelerated relative to a spacecraft and impacts are common, but can cause severe damage. Impacts on fiber reinforced plastics normally lead to delaminations between the fiber layers and the matrix material. The inner damages are much bigger than the visual damage on the surface. Using ultrasound the internal damages can be detected. Nowadays it is common to use non-contact ultrasonic through transmission techniques like air-coupled ultrasound [6] or laservibrometers.

Although a lot of research has been done in aerospace industries, the results can’t be exactly transferred to the use at wind turbine blades. Wind turbine blades are built rougher and the structural elements are much thicker. The flaws to be detected, as described in chapter 2.1, are bigger and of quite a different nature than in common aerospace. Another difficulty is, that the turbine blades usually only are accessible from the outside. Through-transmission techniques are not suitable for this application. Furthermore the inspections have to be done in service and therefore have to work outside and all-weather. Unlike other non-destructive testing techniques, e.g. thermographic techniques [7], acoustic techniques are not as badly affected by temperature or air humidity.

3.2 Local resonance spectroscopy

The local resonance spectroscopy is a technique that is developed to replace the manual tapping test done by experts during regularly inspections at wind turbine blades. The idea is to generate a reproducible sound using an impulse hammer and to record the excited sound with a microphone. Due to the hammer impact, the turbine blade starts to vibrate in a local area around the excitation. The resonance that is generated by the impulse depends on the structure of the vibrating area. Air bubbles and delaminations excite a characteristic sound. The principle of measurement is shown in Figure 3. Several measurements along a defined grid are done and compared to get a picture of the internal health of the wind turbine blade.

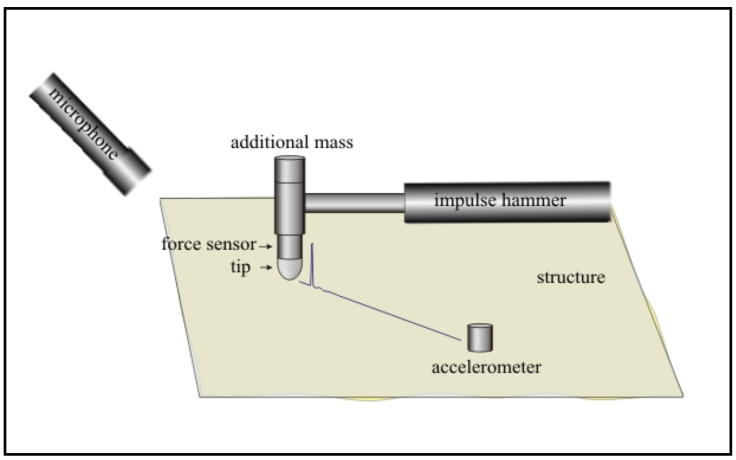

Figure 3: Acoustic resonance spectroscopy

Additionally the exciting force of the hammer is recorded and provides extra information of the internal structure. A similar technique is for example used at the Transrapid test track [4], where the train is inspected every evening using a standardized tool to tap on the surface. The measurements are then compared to previous results measured at the same points. Changes in the signals point to internal damages as delaminations.

An advantage of this technique is the contact free and therefore fast measurement. The technique also works outdoor and is not affected by a wet or dirty surface.

3.2.1 Measurements and Results

The described technique was used at a small test specimen with visible delaminations and cracks. First the excitation signal of the impulse hammer was recorded on different materials. The hammer knocked several times on different areas of intact GFRP, on delaminated GFRP and on the sandwich areas of a turbine blade, where only a thin layer of GRFP was covering plastic foam. The recorded time data and the corresponding amplitude spectra of the force recorded at the hammer are shown in Figure 4. The red curves (middle) correspond to an excitation signal on intact GFRP. The black curves (bottom) show the signal excited on the sandwich areas and the blue curves (top) were excited on delaminated GFRP. First of all it can be seen, that the contact time of the hammer with the surface on intact GFRP is the shortest. The material is hard and not much deformed by the hammer. On the delaminated GFRP the hammer pushes the delaminated layers together and the contact time increases. On the sandwich areas the contact time is longer, compared to the contact time on GFRP, because the material is smoother and the hammer is able to deform it. The excitation signals on delaminated GFRP and the sandwich are approximately the same length. However, differences in the signals are visible and the blue curves seem to be more disturbed. Further investigations and measurements at bigger test specimens have to bring up credible distinctive criteria.

The shorter the contact time, the broader is the excited frequency spectrum. The amplitude spectra therefore are broader for the excitation on GFRP.

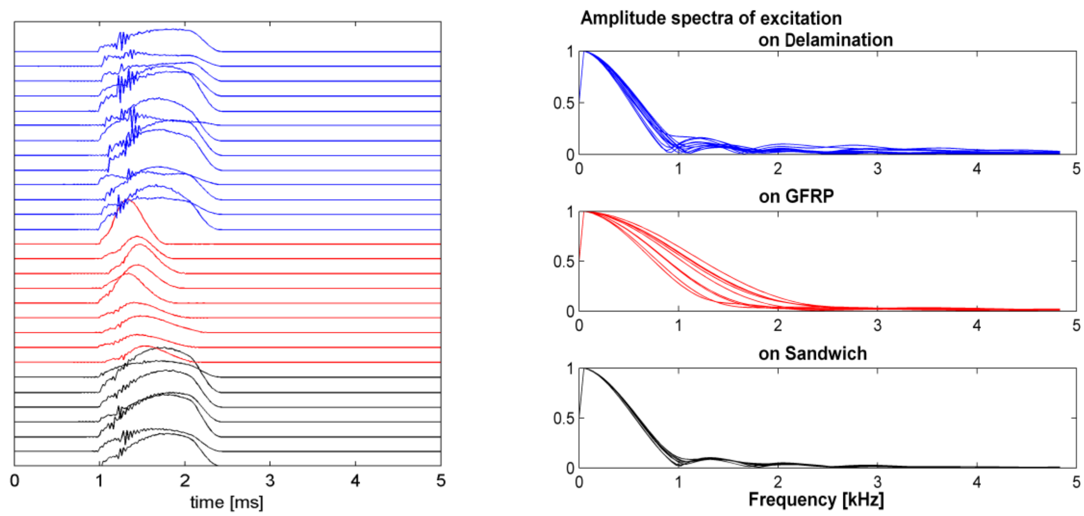

Figure 4: Time data (left) and amplitude spectra (right) of the force recorded at the impulse hammer during an impact. The blue curves (top) show measurements on delaminated GFRP, the red curves (middle) show measurements on intact GFRP and the black curves (bottom) show measurement excited on Sandwich areas.

The excited sound on intact GFRP and delaminated material was recorded using a microphone. 128 measurements along four lines on a damaged test specimen were recorded and the time-amplitude data were transformed to the frequency domain using a FFT. The amplitude spectra of the measurements are shown in Figure 5. The amplitude was logarithmized and is color-coded. Visibly damaged areas are marked in the figures as areas between the black lines. A change in frequency content is visible if the sound was excited on delaminated areas of the test specimen. Compared to the non-damaged areas a rise in frequencies between 2 kHz and 5 kHz can be identified. The difference can clearly be seen between the measurements between the black lines and the measurements with the numbers 97 to 128. The measurements 97 to 128 were done on definitely undamaged material, the measurements between the black lines definitely on damaged material. All other measurements were done on material which seems to be undamaged from the outside. Some measurement also show different frequency content compared to the undamaged material in measurements 97 to 128. It is possible that these areas are damaged too and the damage isn't visible from the outside. To evaluate the technique it will be necessary to get test specimen with known built-in damages. However, the first impression of this technique shows a powerful and easy to handle tool for the inspection of wind turbine blades.

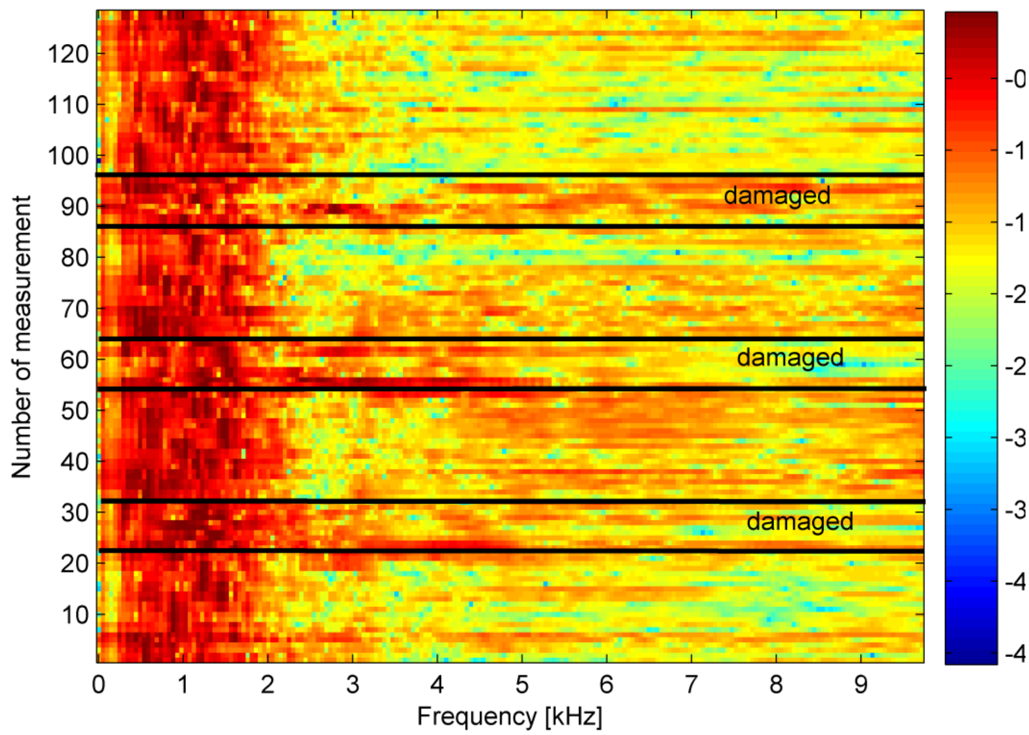

Figure 5: Logarithmic amplitude spectra of the recorded sound at 128 impact points.

3.3 Ultrasound – Echo Technique

Echo-techniques using ultrasonic waves are common and well investigated in NDT [3]. The principle shown in Figure 6 is very simple. An ultrasonic pulse is send into the test specimen using an ultrasonic transducer. The waves are traveling through the specimen and are reflected at the back wall or at flaws within the material. The reflected waves are recorded using the same transducer. A longer travel path results in a later echo. The location of the back wall echo therefore gives information about the thickness of the inspected structure.

This technique will be used to detect areas of missing bond or kissing bond between the belt and the bars within the wind turbine blades. The ultrasonic waves have to travel through several centimeters of GFRP, which is due to the fibers a highly sound scattering and damping material. Therefore a high voltage ultrasonic pulse is used to send enough energy into the material. As acoustic and elastic waves are damped each period, high frequency waves are stronger damped than low frequency waves when travelling along a defined distance. Therefore the use of low frequencies is advantageous for highly damping materials. On the other hand acoustic waves are only sensitive for flaws of sizes that lie in the range of the used wavelength. A feasible compromise between damping and resolution has to be found.

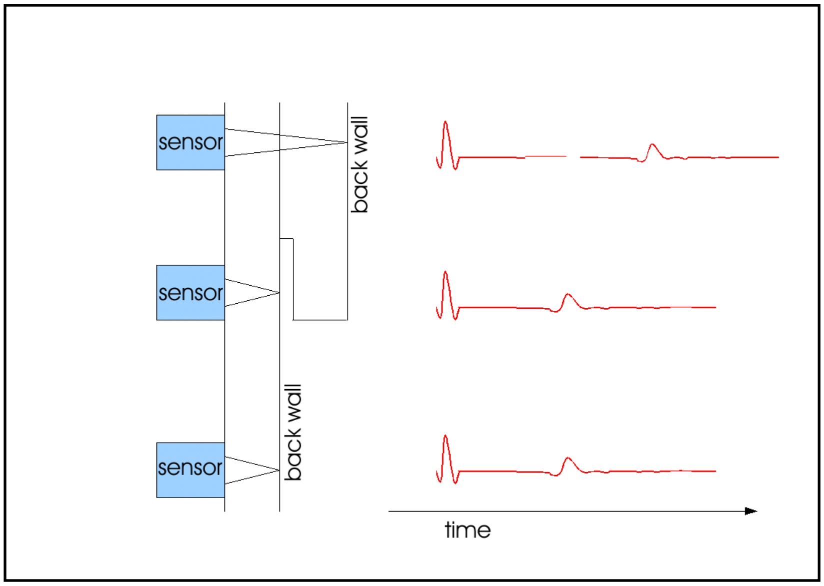

Figure 6: Principle of an ultrasound-echo measurement

The ultrasound-echo technique is supposed to be applied as tool for the regular inspections at wind turbine blades. Therefore the developed system has to be either portable and carried by the climber or fixable at an automatic inspection system. Both would require a small and lightweight system. This comes along with the problem of coupling. Ultrasonic waves are reflected at boundaries between layers with different acoustic impedances. The acoustic impedance of solid bodies is significantly different from the acoustic impedance of air. Therefore a great amount of energy gets lost in the gap between the transducers and the test object. To minimize the energy loss, normally this gap is filled with a couplant like oil or water. The climber or robot would have to carry a big amount of couplant and therefore much weight. Furthermore, the application at the turbine blade the use of a couplant is not possible if a simultaneous use of thermography is desired. Hence, a dry coupling is preferable and possible using special transducers covered by silicon membranes. A constant contact pressure is suitable to guarantee a reproducible coupling.

3.3.1 Measurements and Results

Ultrasound-echo measurements were done at a piece of a wind turbine blade containing the bonding area between belt and bar. The used test specimen is about 50 to 50 centimeters big and is shown on the right in Figure 7. A piezoelectric transducer with a center frequency of 1 MHz and a high voltage pulser/receiver was used. Three lines with measuring points every 3 centimeters were investigated. The three lines are shown in Figure 7 on the right. It is necessary that the points of measurement have an adequate distance to the edges of the test specimen, because reflections from the edges can distort the results. An ultrasonic pulse was generated at every measurement point and the reflected waves were recorded. For the visualization the data were normalized and the squared amplitudes are shown color-coded in Figure 7 on the left. Additionally a side view of the test specimen was added to match the data with the object.

The measurements started from the right end of line 1 and are numbered in the figure. Measurements 1, 2, 7 and 8 in each line were done on the GFRP without attached bar. In line 1 and line 3 this measurements show much reflected energy at about 16 µs. The sound velocity of the GFRP was determined in a separate experiment to 2700 m/s. The echo at 16 µs therefore belongs to an impedance boundary at about 2 cm, which is obviously the back wall echo. This clear back wall echo disappears in the area where the bar is attached. The traveling sound waves dissipate in the plastic foam the bars are made from. The absence of the clear back wall echo in comparison of adjacent points allows a statement about the quality of the bond.

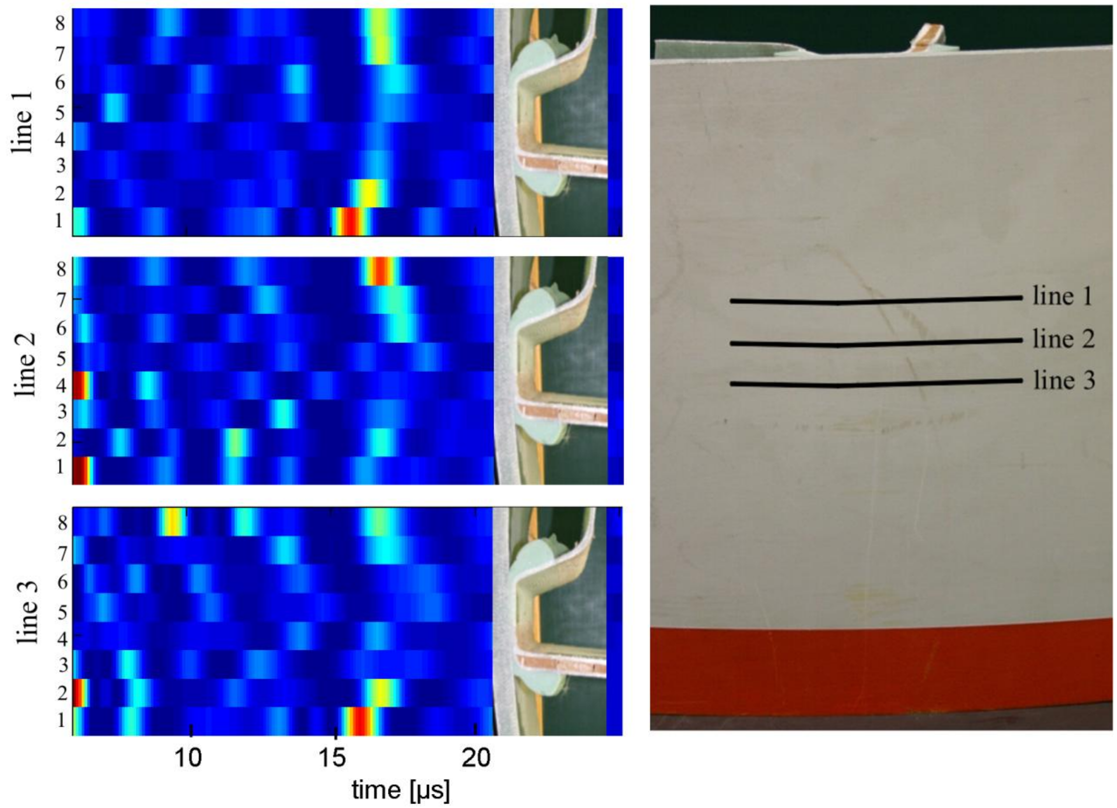

Figure 7: left: energy of the back wall echoes for three measured lines across the bond between bar and belt. Right: Picture of the test specimen and the three lines.

However, measurement line 2 does not show the difference between bond areas and pure GFRP as clear as the two other measurements. Maybe this was an effect of a badly coupled sensor. As described above the coupling of ultrasonic transducers is a known problem. To guarantee a reproducible coupling the contact pressure between transducer and surface will be held constant in future measurements using a pneumatic system and a load cell.

4. Conclusions

Two acoustic techniques for the inspection of wind turbine blades were shown in this paper. Both techniques have the advantage to work without a contact couplant or even contact free and the developed equipment will be small and lightweight. This makes the system portable even for an industrial climber or enables the system to be attached to an automated inspection unit like a robot. Thus, an in-service inspection without a demounting of the turbine blades is possible. A simultaneous measurement using infrared thermography is conceivable and would be a sensible completion to the acoustic techniques.

The local resonance spectroscopy is able to replace the common manual tapping tests. First measurements showed that flat delaminations within the GFRP can be detected using this technique. In addition to the recorded sound the exciting signal at the impulse hammer can give information about the internal structure of the inspected area. Measurements at bigger test specimen and under realistic conditions will prove the practical application of the technique. Furthermore the analysis algorithms have to be optimized to build reliable inspection equipment. However, the technique seems to be reasonable for the inspection of wind turbine blades.

The ultrasound-echo technique is able to check the bonding areas beneath thick GFRP-laminates. The technique was applied to parts of real wind turbine blades. Changes in the echoes of the ultrasonic signals point to bond or misbond of the adhesive areas. This knowledge is very important, because bad bonding is a major problem for the safety of wind turbine blades and nowadays can't be detected dependably during the regular inspections. More measurements at specimen containing realistic flaws will be done. Small and portable measurement equipment will be built and the analysis algorithms will be optimized to create a easy to handle measurement system that can be applied without further knowledge in NDT techniques.

It has to be marked, that both techniques do not and don't have to work as absolute techniques. A statement of the internal condition of the wind turbine blade is done by a comparison of adjacent points and the knowledge of the principal construction of the blade. It has to be assumed that the exact internal structure of wind turbine blades depends on the manufacturer and will not be known. A comparative technique will be able to find the location of the bonding areas even if it is only known by tenth of centimeters. Both techniques are able to help to make wind energy safer and reduce failures of wind energy plants.

References

1. Directive 2001/77/EC of the European Parliament and of the Council of 27 September 2001 on the Promotion of Electricity produced from Renewable Energy Sources in the Internal Electricity Market. *Official Journal of the European Communities* 2001; **L 283**, 33-40.
2. Gesetz zur Neuregelung des Rechts der Erneuerbaren Energien im Strombereich. *Bundesgesetzblatt Jahrgang 2004*; Nr 40, Teil 1, 1918-1930.
3. Große CU. Akustische Verfahren zur zerstörungsfreien Prüfung von Baustoffen und Bauteilen. *Habilitationsschrift (habilitation thesis)*, University of Stuttgart, 2005, 150 p.
4. IABG http://www.iabg.de/transrapid/leistungen/diagnose/delamination_de.php Stand 21.03.2008
5. Lading L, McGugan M, Sendrup P, Rheinländer J, Rusborg J. Fundamentals for Remote Structural Health Monitoring of Wind Turbine Blades – a Preproject. Annex B – Sensors and Non-DestructiveTesting Methods for Damage Detection in Wind Turbine Blades *Risø National Laboratory*, Roskilde, Denmark, 2002
6. Peters J, Kommareddy V, Liu Z, Fei D, Hsu D. Non-Contact Inspection of Composites using Air-Coupled Ultrasound. *AIP Conference Proceedings* 2003, **Vol. 657**, 973-980.
7. Rumsey MA, Musial W. Application of Infrared Thermography Nondestructive Testing during Wind Turbine Blade Tests, *Journal of Solar Energy Engineering* 2001, **123**, 271.
8. Sutherland H, Beattie A, Hansche B, Musial W, Allread J, Johnson J, Summers M. The Application of Non-Destructive Techniques to the Testing of a Wind Turbine Blade. *Sandia Report* ***SAND93-1380***, 1994, Albuquerque.