Lightning Safe Rotor Blade Monitoring Using an Optical Power Supply for Ultrasonic Techniques

B. FRANKENSTEIN, D. FISCHER, B. WEIHNACHT
and R. RIESKE

ABSTRACT

To provide a safe and reliable technique for rotor blade inspection, the lightning damages caused by any metal equipment inserted into the blade have to be eliminated. This paper, therefore, deals with an approach that consequently avoids any metal cables by applying optical fibers both for data communication as well as for the power supply.

The used sensor network is specialized in acoustic emission and acousto ultrasonic techniques. The sensors are located in areas of the blade where failure often occurs. The acoustic signals caused by failures in the blade are constantly recorded and evaluated regarding criteria like energy content and travel time.

The optical power supply is realized by a laser source, an optical fiber for the energy transfer, an optical receiver and a communication fiber with receiver and transmitter. The optical power transmitted over one fiber equals approx. 1W.

INTRODUCTION

Monitoring of windmill rotor blades is usually based on measurements of eigenfrequencies of the blade and the quantifying of changes over time or, more sophisticated, by operational modal analysis. Systems realized by Woelfel or IGUS are examples of such systems mainly focussed on ice detection by supporting also damage detection. The alternative use of acoustic techniques like acoustic emission and acousto ultrasonics are helpful for rotor blade structure monitoring. The IZFP is developing and applying these techniques for several years. The defect detection presented is based on full scale fatigue tests in test beds of IMA Dresden and Nordex in Rostock. The disadvantages of these techniques are the large number of sensors necessary for localizing defects. Because of the high damping of GFRP laminates, the maximum distance between sensors are limited to 3…5 meters depending on the laminate thickness. For a holistic monitoring of the entire blade, a sensor network like presented in Figure1 has to be applied.

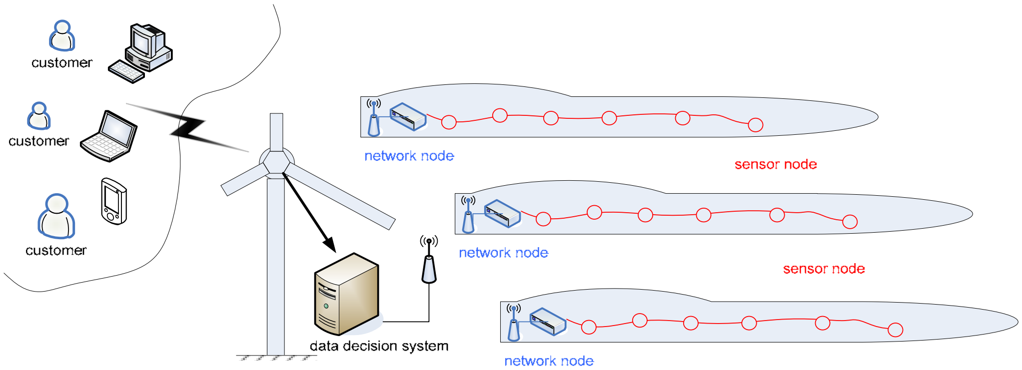

Figure 1 System overview – principal building blocks of optically interconnected sensor system star structure

Since wind turbines are usually situated at exposed sites, the risk of flash lightning is high. Especially the rotor blades serve as potential striking points. The frequency for lightning strikes lies at 4 lightning strikes per year and wind turbine in Germany. The rotor blades are involved at over 50%.

To protect the rotor blades, receptors are integrated at the tip of the blade. This defined striking point is attached to a lightning rope which is connected to the earth electrode via hub, slip ring and tower bottom.

In the case of lightning, the current in the lightning rope causes an electromagnetic field which might also induce an electromagnetic field in parallel guided metal conductions serving as introduction coils. In order to avoid damaging, a minimum distance to the lightning rope has to be assured depending on the cable length. This distance not only avoids the destruction of sensitive electronics but also an overheating of the cable by induction currents and a resulting ignition of the blade.

For the development of a sensor network, this limitation has to be considered regarding number and location of the single sensors for acoustic principles and usually is contradicting to the lightning protection requirements. So, conventional metallic conductors are limited in their application possibilities in wind turbine rotor blades. Alternatively, energy harvesting systems can be applied that generate the energy from vibrations of the rotor blade. The energy is transferred by wireless systems. Due to the high data rate for the AE measurements and the demand of a continuous monitoring, this solution is connected with high costs. The only possible solution at the moment seems to be the continuous transfer of power in the range of 50mW. Optical solutions can easily be attached to the laminate and even be integrated. The optical fibers can as well be used for the communication and the energy supply.

SENSOR NETWORK WITH OPTICAL CONNECTIVITY

Figure 2 depicts the schematic set-up of the monitoring system’s hard ware. It consists of a power laser module, which supplies the optical power and an optical network unit for collecting and processing the received sensor data. These modules are located in the hub or the blade’s root.

A number of sensor nodes are distributed across the entire rotor blade to form a sensor network for holistic damage monitoring and damage location. For the prototype system, with the demand for easy installation and testing, the connection between the sensor in the rotor blade and control electronics in the hub is established by a two-part optical fiber cable harness. This glass fiber optical harness consists of a breakout optical terminal block with two multi-fiber ribbon cables. The terminal block is fixed at a central position inside the rotor blade and then connected to the control electronics in the hub. These two connectors will be sealed upon installation to ensure safe laser operation. From central breakout point the sensor pigtails are connected via special fiber connectors with metal protection shutters that conform to the highest safety requirements for all laser classes. Further developments would rely on a dedicated single part optical harness with the aim to reduce or completely omit optical connectors and hence increase the reliability. Due to the complete galvanic decoupling the of the sensor nodes no limitation for positioning the sensors occurs. Electromagnetic disturbance has no influences to the optical interconnection and they have a lower weight compared to copper wires

Each sensor node is equipped with a photovoltaic power converter, which supplies the sensor electronics with energy, and a surface emitting laser (VCSEL) for ultra low power communication. Dedicated sensor electronics for signal processing have been developed for operating the PZT sensor

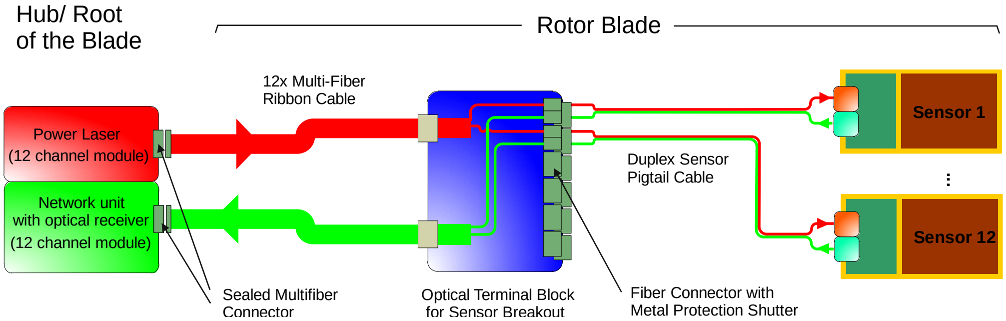

Figure 2 Schematic of monitoring system hardware with optical power supply and data communication

Optical Power Supply Unit

The optical power supply unit is built up with high power 830nm fiber-coupled laser diode sources. These laser sources are commercially available and widely applied e.g. in printing industry, night vision and optical pumping. Due to experiences gathered in this wide application, these lasers are among the most reliable semiconductor laser sources available and therefor can achieve a long-life cycle even for continuous operation. The challenge was to develop an optical power supply unit that handles the extreme environmental conditions, for example in the forecasted off-shore application. For a long laser life-time the thermal management is most crucial, while natural convection with no moving parts is essential for reliable operation.

The prototype version of the optical power supply is shown in Figure 3a), while Figure 3b) illustrates the main components of the unit. A trade-off between active and passive optical components has to be made. The prototype contains a laser bench with six fiber-coupled lasers, each being able to emit a maximum of 1W of optical power at 830nm. The optical output of each laser is split into two fibers by 1-by-2 fiber-optic fused couplers (50%/50% or 3dB). With this comparatively expensive sample set-up, the lasers are operated far below the maximum output power – giving enough headroom for readjusting and longer life-time by lower thermal stress. Further optimizations will include the minimization of (more powerful) active components that will be replaced by a cascaded coupler network with more passive power splitters. Two 2W fiber coupled lasers with a two stage power splitting by one 1x3 followed by three 1x2 couplers would suffice the optical power needs.

As mentioned before, an active temperature control is required to operate the lasers within their specified operating temperature. Therefore the laser bench is placed onto a cold plate with thermo-electric coolers (peltier elements). The temperature control works in bipolar operation, meaning it can also heat the laser in case of very low ambient temperatures.

The laser driving electronics combines the necessary constant current source with protection circuits. The laser operation is only enabled when the programmed temperature limits are maintained. This way thermal damage to the sensitive lasers is widely avoided.

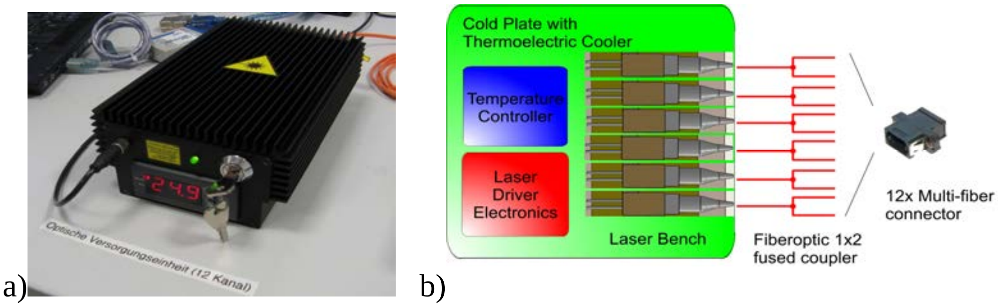

Figure 3 Optical power supply unit for 12 sensor nodes; photograph of prototype (a) and functional block diagram (b)

Network Unit

Next to the optical power supply unit, also in the hub or root of the blade, the central network unit is located. Its task is to collect the sensor data that are optically transmitted from each sensor. This unit comprises commercially available 12-channel parallel optical receivers to convert the optical data signal into equivalent electrical signals.

In Figure 4 the Network unit with its principle operation is demonstrated. The optical data stream of the 12-channel fiber ribbon cable is butt coupled to the 12-segment photodiode array of the extremely compact receiver with integrated amplification and signal recovery. Each channel generates an electrical signal which will be amplified, filtered and then reconstructed to a pure digital signal with a comparator. Afterwards, the digital signal stream is decoded and finally reconstructed to the real analog sensor data. These optical multi-channel receivers are state-of-the-art in parallel computing and perfectly match the needs of optical sensor networks as of high channel density, low cost and modular system architecture.

One central network node, as demonstrated in Figure 4 can support up to 48 individual channels and receive/ compute their data simultaneously. It is also linked with the power unit by an RS-232 link in order to broadcast configuration data, which will be modulated atop the DC power signal.

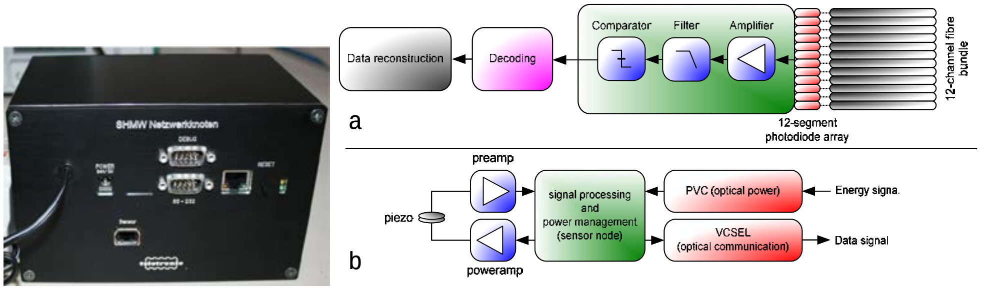

Figure 4 Network unit prototype and block diagram and operation function of network unit (a), and sensor node (b)

The three network nodes from each rotor blade communicate via an Ethernet link with the hub computer, which buffers the sensor data and relays them via PowerLAN or wireless LAN to the nacelle and via the existing data link to the processing and analyzing computer at the windmill's tower base.

Sensor Node

Figure 5 displays the final prototype version of the fully featured sensor node with optical connectivity. For supplying the sensor electronics of every sensor with electrical power special photovoltaic converter (PVC) are used to efficiently transform laser light into electrical energy. The PVC receives the photons from the high power laser source and generates electrical charge carriers inside the GaAs chip and hence an electric power. The overall continuous power consumption for all functionalities of the entire sensor node was optimized within many iterations down to approximately 40 mW. Even though more optical power could be delivered by the lasers, this was found as the initial optimum working point without too complex specifications.

In order to minimize the overall electrical power consumption of the sensor, the optical communication with standard components turned out as one main consumer. An ultra low power surface emitting laser (VCSEL) was chosen as light source for its supreme reliability and best optical coupling efficiency. This laser has a very low laser threshold current and thus a very low electrical consumption. In the active mode the light source only needs an electrical power of approximately 2 mW. Usually, an extra laser driver circuit is needed to drive a laser. In this case such a driver is not necessary because the light source can be directly driven by the current output of the signal processing unit.

Figure 5 Complete realization of a sensor node with PZT sensor (red) and a duplex optical fiber cable for optical power supply and communication (blue)

The sensor works both as a structure-borne sound sensor and as a ultrasonic sound source as an actuator and additionally packs an temperature sensor as well as a MEMS accelerometer with all analog and digital electronics for signal conditioning and communication.

APPLICATION RESULTS

The main challenges when applying the acoustic emission (AE) and acousto ultrasonics (AU) technique within the framework of a full-scale fatigue test or on a rotating system, result from the strong ambient noise level on one hand and the unfavorable acoustic properties of the composites on the other hand.

Thus, the data acquisition system and the evaluation software have to meet the following requirements:

(a) Due to the highly increased intrinsic attenuation of the CFRP (about 10 dB/m) the wide-meshed sensor pattern can only detect low-frequency lamb wave packets, particularly the A0 component. Therefore, a high sensitivity of the sensors in this frequency domain as well as an increased dynamic range of the A/D converter is required.

(b) The localization accuracy is limited because of the high dispersion of the asymmetric wave modes and the velocity inhomogeneities due to varying material thickness. Therefore, a respective error diagnosis has to be integrated within the source localization algorithm.

For acousto ultrasonics techniques, high power transducers for exitation of acoustic waves is additionally required.

The applied algorithms for AE are based on the arrival times and the choice of the channels around the trigger. The development drawing of the 3-D model of the rotor blade was realized in order to calculate the source points of the acoustic emissions in plane coordinates and the retransformation of these coordinates into the three-dimensional model.

Figure 6 shows the localization plot from AE measurements of the rotor blade. The number of all detected hits per unit volume is marked in color. They document sufficient localization precision for being able to give structure statements. The influence of the shear webs on the acoustic emission regime in the rotor blade is visible. Because of the exitation by an excenter-swing-machine directly on the blade, high acoustic emission densities could be detected caused by the friction of the machine on the surface of the blade. This does not refer to damages in the blade.

In the end of the fatigue test, a crack could be detected at 17.5 m. The position of the fatigue crack is marked in black. The acoustic emission events were detected on both sides of the crack due to the increasing fatigue and the loss of adhesion between the web and the aerodynamic shell (debonding). In the surroundings of the debonding of shear webs acoustic emission events were increasingly located which point at stress redistributions in the rotor blade.

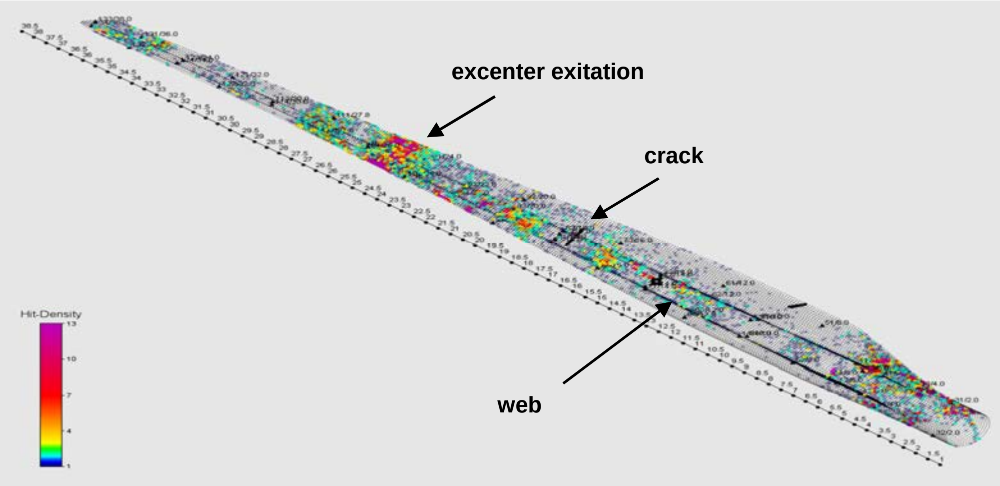

Figure 6: AE localization plot of a 40 m rotor blade during the full-scale fatigue test, hits per unit volume in color, initial application determination by means of correlation of signal windows, 41 772 hits

Figure 7 shows the last phase of the fatigue test when the cracking occurred. This figure is higher scaled than Figure 6. The cracking process is clearly indicated by the high AE rate marked in red. The acoustic emimissions caused by stress redistribution and debonding of shear webs is to be seen on both sides of the crack.

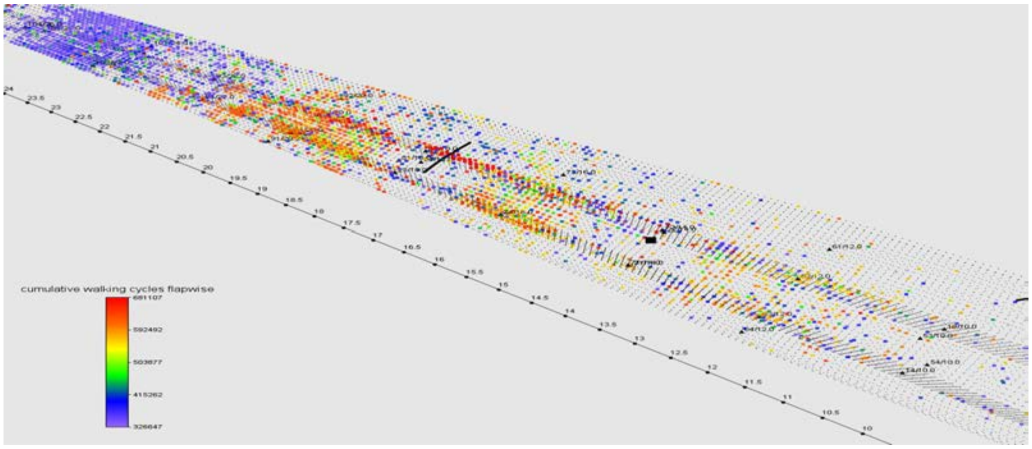

Figure 7: higher scaled AE localization plot during the full-scale fatigue test of a 40 m rotor blade, crack detection visualized

Figures 8 and 9 show the results of the AU measurements. They were carried out in fixed intervals during the fatigue test with no excitation. The sensors are marked in black and the travel pathes were coloured regarding signal damping and therefore the damaging process of the structure. The entire sensor network consisted of 52 sensors distributed over the blade by triangularly taking into acount the blade design and the resulting boundary conditions.

The Acousto Ultrasonic (AU) measurements were carried out in a baseline mode. Each of the 52 sensors can work as actor too and were excited with a raised cosine (4 periods) with centre frequency of f_c=24 kHz. After receiving of the signals low- and high pass filtering were applied. The signals were processed considering the changing in amplitudes in wave packets for each different travel path. The colour scale in Figures 8 and 9 refers to amplitude changes in signals (green-no changes, red-significant changes).

Figures 8 and 9 refer to different fatigue states (Figure 8: 417146 edgewise cycles and 326647 flapwise cycles; Figure 9: 417146 edgewise cycles and 681258 flapwise cycles). The damaging process was developing during the experiment especially because of the shear web debonding as already mentioned. Comparing Figure 7 and Figure 9 the progress in damaging prozess before cracking are described well by both methodes. There is a high AE activity next to the crack because of stress redistribution and a significant changing of AU trafel pathes as well.

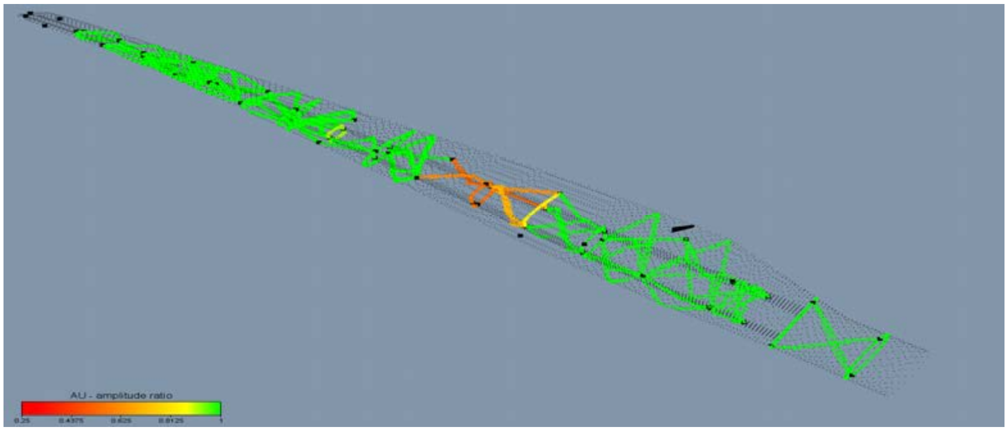

Figure 8 Results of acoustic ultrasonic technique (change in amplitude after excitation of lamb waves) after 417146 edgewise cycles and 326647 flapwise cycles

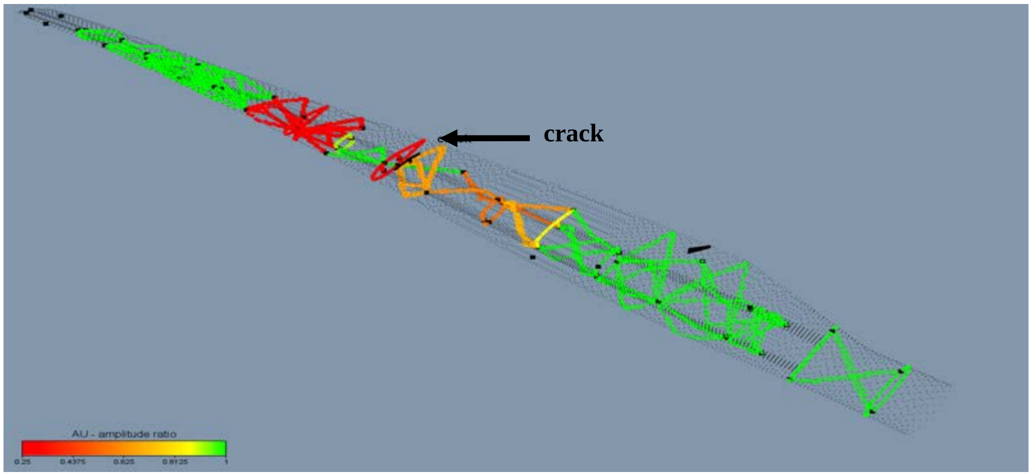

Figure 9 Results of acoustic ultrasonic technique (change in amplitude after excitation of lamb waves) after 417146 edgewise cycles and 681258 flapwise cycles

The measurement results confirm the fundamental qualification of the acoustic measurement and analyzing system developed for the permanent monitoring of rotor blades with complex blade geometries and material parameters. In ongoing projects, the sensitivity of the AE system is improved by an optimized layout of the sensor network.

SUMMARY AND OUTLOOK

The presented results from a testbed test series indicate that the results of AE and AU strongly correlate with fatique of and damages in rotor blades of wind turbines. AE measurements are very suitable to not only quantify but also localize the source of acoustic transmitted waves and, therefore, the damage/defect area. AU measurements show a high potential to detect the damaging process and the results of damaging. They allow for estimation of the fatique state of the rotor blade. The resolution depends on the distances beween the sensors because only entire travel pathes can be evaluated.

To apply this monitoring system, the lightning issue demands for a copper free power supply solution. The authors suggest an optical power supply system with an exclusively optical transmission system to avoid any metal cables. The communication is also realized by only optical fibers.

Future works will be focused on the transmission of a prototype system to a rotating wind mill to investigate results of acoustic mesurements with the standard parameters of windmill instrumentation like wind speed and issues like durability, reliability, maintenance and environmental influences. The goal is to transfer the system to industrial applications within the next two years.