Rotor Blade Monitoring – The Technical Essentials

*Holger Söker, Deutsches Windenergie-Institut GmbH, Ebertstr. 96,
D-26382 Wilhelmshaven, Germany, Tel. : +49-4421-4808 –25, Fax: +49-4421-4808-43, h.soeker@dewi.de*

*Dr.-Ing. Antje Berg-Pollack, Fraunhofer Center Windenergie und Meerestechnik, Am Lunedeich 158, D-27572
Bremerhaven, Tel: +49 (0) 4 71 / 90 26 29 – 30, Fax: +49 (0) 4 71 / 90 26 29 – 19, pollack@cwmt.fraunhofer.de*

*Christoph Kensche, Fraunhofer Center Windenergie und Meerestechnik, Am Lunedeich 158, D-27572
Bremerhaven, Tel: +49 (0) 4 71 / 90 26 29 – 20, Fax: +49 (0) 4 71 / 90 26 29 – 19, kensche@cwmt.fraunhofer.de*

Summary

Market introduction of rotor blade condition monitoring systems has significantly caught on. Several systems based on different sensor technologies and applying different signal evaluation schemes are promoted at present. The approaches taken for blade condition monitoring are found to be defined by the background of the system manufacturer. The systems try to extrapolate established condition monitoring techniques like structural vibration monitoring to the component *rotor blade.* In other cases advanced and promising sensor technologies are suggested together with rather complex and demanding on-board IT-requirements that allow for quite differentiated condition statements. The paper gives a user's view on typical systems and tries a structured approach to the essentials of rotor blade condition monitoring. Possible condition statements are highlighted s.a.

- the instantaneous operation / loading condition
- the structural health condition
- the residual life time

and are found to have decisive influence on the choice of the techology to use s.a. vibration sensors, fibre bragg sensors, structure integrated (acoustic, optical) sensors.

Introduction

Market introduction of rotor blade condition monitoring (RBCM) systems has significantly caught on. Several systems based on different technologies are promoted at present. The range streches from rather conventional vibration monitoring technology using accelerometer via more innovative fiber optic strain measurements to highly sophisticated acoustic monitoring technologies like acoustic signature analysis and and acoustic emmision techniques.

The approaches taken for blade condition monitoring are found to be somewhat defined by the background of the system manufacturer. In general the systems either try to extrapolate established condition monitoring techniques to the component *rotor blade* or in other cases advanced and promising sensor technologies form the basis of the system. The condition statements of the systems are at the same time focussed on different aspects of RBCM.

Risk Assessment

Before all, appropriate knowledge on the potential risk connected with operating wind turbine rotor blades is essential [1]. Assessment of the risk including severity of the consequences in case of rotor blade failure provides guidance on what would be the most important condition statement required.

Evaluation of the Wind Energy Report 2005 by ISET [2] reveals that MTBF (Mean Time Between Failures) is 5 years. This means that statistically 20 out of 100 turbines will be suffering a blade failure in one year of operation. Furthermore ISET reports 7.3 lightning bolts events per 100 wind turbine in one year - 28% or 2 are hit directly

Taking into consideration that onshore average downtime for blade repair is 4 days [2] and knowing that this can easily grow to a month's perid in off shore cases the loss in production may be something between 10.000,-- € onshore to 100.000,-- € offshore – not considering cost of repar or replacement itself.

Typical damages in rotor blades as observed in the past:

- cracks in trailing edges [3]
- debonding of / cracks in adhesive joints (e.g.trailing edge, spar to shell)
- local delamination after thunderbolts
- local buckling of structural elements [4]

Possible root causes of these damages in rotor blades are:

- design deficiency (e.g. edgewise vibrations in 600 kW class stall controlled wind turbines)
- undetected production / material deficiencies (especially badly bonded joints)
- inadmissable loading / relative overload (e.g. too large deflection, inadmissable vibration)
- rather wide scatter of the material properties for FRP used in rotor blades [5]

Note: Failure due to material fatigue through nominal loading has not yet played a major role in reported rotor blade damage events. At present rotor blade designs do allow for only 0.35% strain (tension) in the structures as opposed to 0.6% in other industrial applications like aerospace industry. This is due to the requirement on the rotor blade design to avoid inadmissable deflections.

Condition Statements & RBCM System requirements

To enable a more structured approach to the implementations of rotor blade condition monitoring it is indispensable to answer the question: *What is the actual condition statement sought?* Depending on the possible answers to this question the requirements for a blade condition monitoring system may be defined.

The blade’s condition may be expressed in the context of:

1. the instantaneous loading (strains, derived moments and forces) condition
2. the structural health condition
3. the residual service life before failure

Items 1) is required for instantaneous actuation on operational loads on the rotor blades and may be required for adaptive / individual pitch control schemes [6].

Item 2) focusses on the detection of damages, their location and their severity at any time of the blade’s life.

Item 3) - residual life estimation - appears to require information gained from items 1) and 2):
In case no structural health problem has been detected and the cumulative loading of the component throughout the passed operating time may be related to the material strength information enabling an estimate of the life time consumption at the time of analysis. This life time consumption may be compared to the total life time consumption when applying the design load spectrum.

On the other hand *maturity, complexity, robusteness, ability to interface with the turbines operating/SCADA system* and *cost-benefit ratio* form important properties of a monitoring system. A special focus is to be set on survivability of the system or at least its cumulative information content in case of lightning (flight recorder functionality).

Rotor Blade Condition Monitoring System Techniques

Structural Vibration Monitoring (SVM) Techniques

The idea is that damages and damage growth will affect structural stiffness and hence shall appear as changes in the structural vibration modes. Application of accelerometers and gyros in MEMS (Micro Electronic Mechanical Systems) allows to assess transitional and angular accelerations at specific positions in the rotor blade structure. From these measurements the rotor blade vibration mode shapes can be determined by output-only modal analysis [7] i.e. estimation of the mode shape without knowing the load history causing the vibration. This method has been tested by RISO in 2001 and has shown the potential to identify mode shape changes due to damages in the rotor blade structure. The principle is to compare the reference mode shapes of the undamaged rotor blade continuously to those found during operation. The degree to which damages can be detected in size and location is depending on the number and spacing of sensors in the rotor blade structure. For determination and comparison a data processing unit is required. Depending on the instrumentation it may be possible to compute the blades instantaneous load condition using an onboard blade model. The authors are not aware of an application of the mode shape analysis technique for rotor blade monitoring with reportings of specific results.

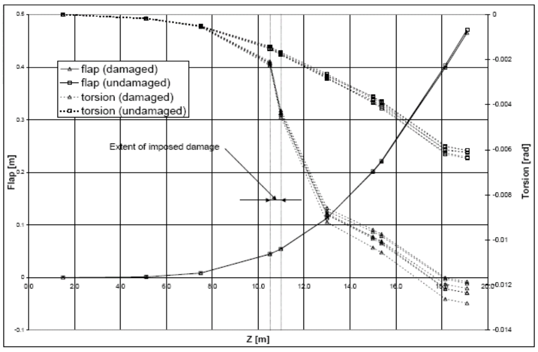


Fig. 1: RISO – Investigation on Mode Shapes for Damage Detection – Flap and Torsion component for 1^{st} flap Mode Shape [7]

Other SVM techniques rely on spectral analysis of the measurement signals obtained from a differing number of accelerometers in the blade. The vibration signal is fed through some filtering and FFT analysis before it becomes possible to compare the on-line spectrum to the reference spectrum of the undamaged blade [8]. The comparison is done by subtracting the reference spectrum from the on-line spectrum. It is assumed that changes in the frequency response of the structure – caused by changes in the blades stiffness – can be identified in the difference spectrum and attributed to specific damages. This proposal is closest to the techniques used in gear box monitoring, where the technique has a proven record. However, while in gear box monitoring the target frequencies that indicate specific damages are well known and can be derived analytically from calculations. The suggested scheme has to rely on a knowledge base that is yet to be empirically established for each new blade type or combination of blade type and *turbine* (here „turbine“ even refers to a new control scheme in the same turbine)

Fig. 2: – Spectrum Analysis Technique: FFT-Spectrum of Damaged Blade (Top), Spectrum of Sound Blade (Middle), Difference Spectrum [8]

Both methods require some „calibration“ as initially the changes in mode shapes or spectral response associated with a given damage are unknown and have to be „learned“ by the system. To a certain degree it has been proven to be possible to simulate damaged structures‘ modal shapes employing numerical computational models of the rotor blade. This calibration has to be validated in an initial phase and if necessary repeated if specific structural and operational parameters of the wind turbine are changed. For the spectral analysis technique a number of tests with artificially damaged blades have been done for calibration.

Structural Load Assessment Techniques

Conventional strain gages or optical fiber bragg grating sensors are installed into the blade structure (either interlaminar or retro-fitted) at a number of measurement cross sections to measure local strains in edge- and flatwise directions. Based on these measurements and using a numerical model in a local (per blade) data processing unit the external and internal loads in the measurement cross sections and several other watch sections are computed. This allows to analyse local strains and strains in watch points as well as mode shapes.

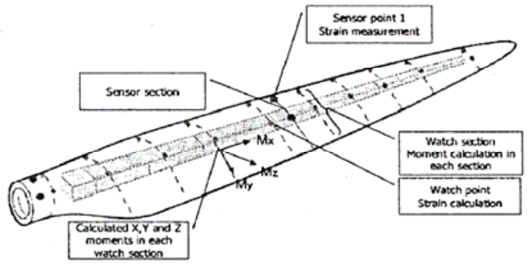


Fig. 3 LM-Blade Monitoring Scheme: Employing Sensors and Computer Model to Calculate Moments and Strain in Watch Sections

The data can be used for overload monitoring, modal analysis, and damage calculations at strain level for life time consumption estimation [9].

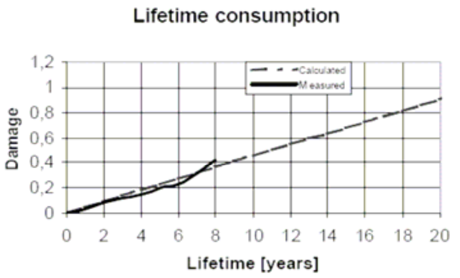


Fig. 4: Lifetime Consumption Plot [9]

Furthermore cumulative on-line load spectra may be derived for comparison with the design spectrum (at a given cross section) and for comparison with load spectra obtained from other wind turbines of the same type operating at specific sites (e.g. inside wind farm, in complex terrain) [10]. Such preventive load monitoring has been developed and proposed by DEWI since 1994.

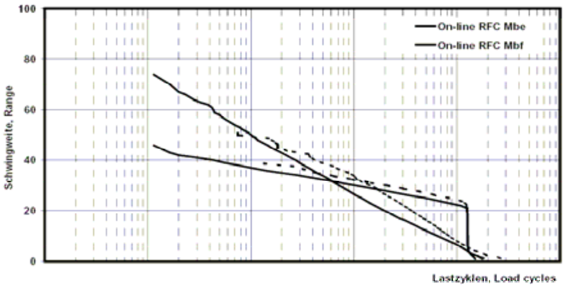


Fig. 5: Cumulative Fatigue Load Spectrum Comparison [10]

Structural Health Monitoring Techniques

A simple crack detection system by LM [3] is based on a set of three optical fibers in the trailing edge of a rotor blade. When a crack is intiated and propagates through the trailing edge in cordwise direction it will first cut the fibre closest to the trailing edge and then with further progress of the damage also the second and third optical fiber each time indicating a higher degree of urgence to act.

Promotors of true structural health monitoring techniques consider it impossible to *predict* damage developement in terms of exact type and location of the damage on the basis of load condition information (measurements / numerical simulations) [5]. This is attributed rather to the large scatter in material properties than to the uncertainty in the knowledge of the loading.

Opposed to local techniques s.a. strain gages (fiber optic or conventional) and other optical crack detectors SHM techniques apply „global“ monitoring as the sensors „listen“ into the structure and analyse the detected acoustic vibrations in the kHz frequency range.

Two basic approaches may be differentiated:

- Passive SHM using only receiving sensors to analyse the acoustic vibrations inside the material. The basic principle is that materials exposed to a loading process emit sound waves created by sudden changes in the structure i.e. formation of cracks.

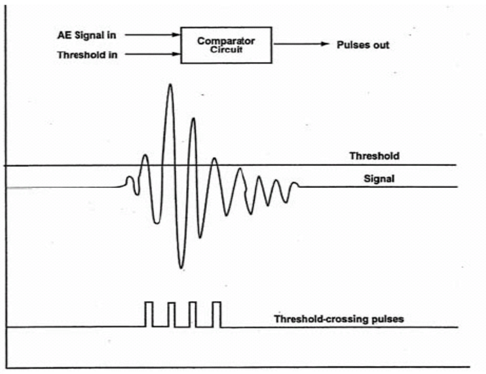
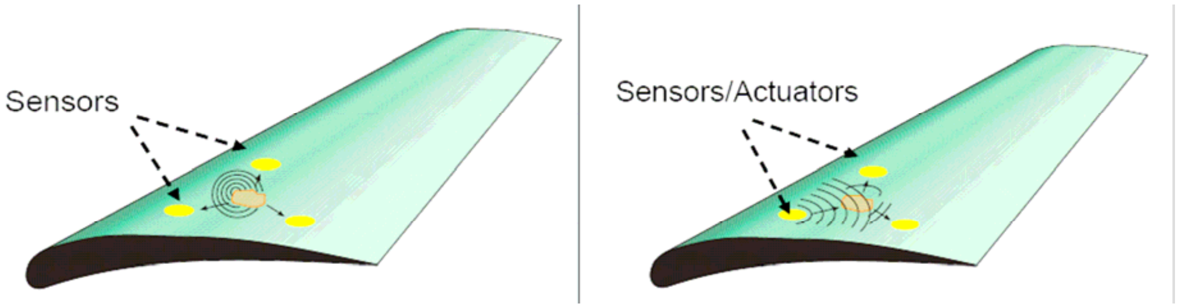
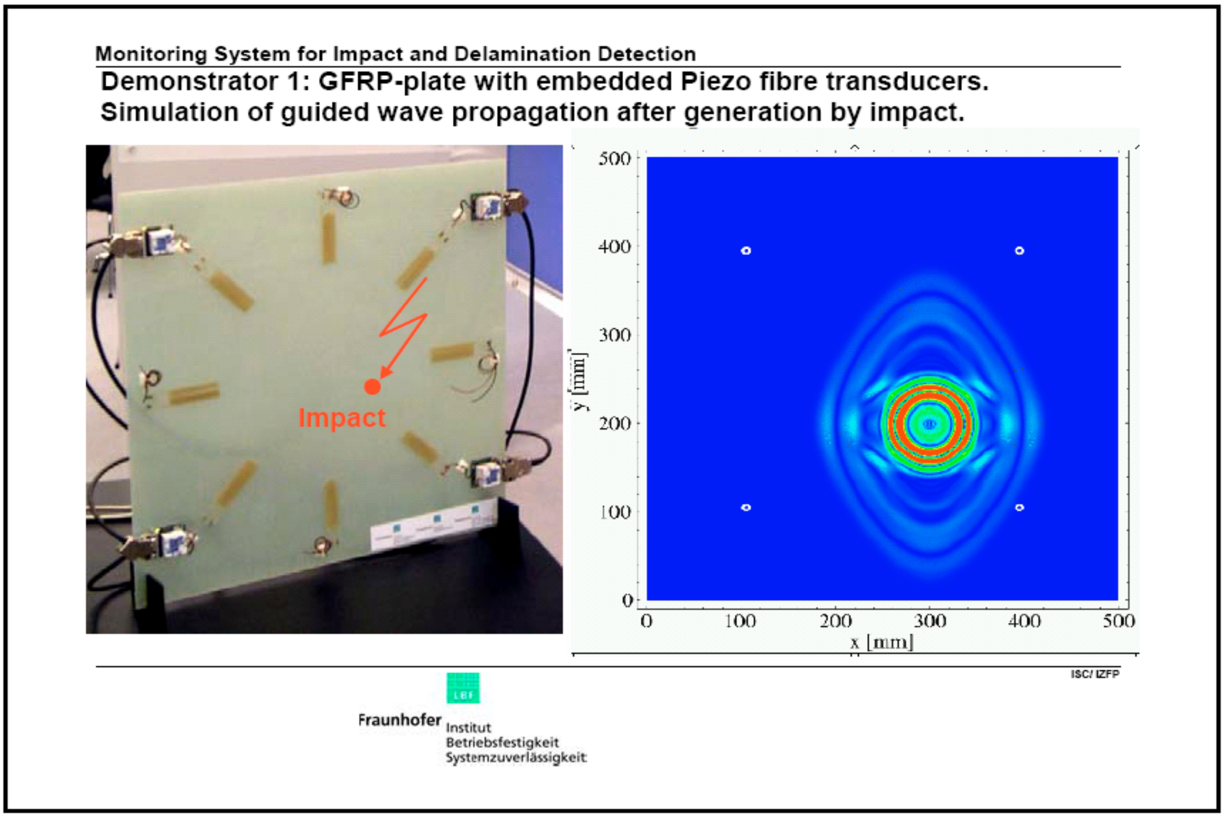


Fig. 6: Acoustic Emission: Signal Detection and Threshold Counting Scheme [5]

- Active SHM using piezo fibre composite-modules [11] acting as both, sensors and actuators. By using pulse-echo or acoustic signature techniques, scattered waves from inside the structure or changes in acoustic signature response can be detected and used as damage indicator. Several piezo fibre transducers may be used to span a monitoring area in which elastodynamic wave fields can be focused to specific control volumes of the structure by temporally delaying excitation and detection of individual actuators and sensors.




Monitoring System for Impact and Delamination Detection

Demonstrator 1: GFRP-plate with embedded Piezo fibre transducers.
Simulation of guided wave propagation after generation by impact.

Fig. 7: Acoustic Signature Scheme [11]

Conclusion

The conclusion from the above user’s investigation into the blade monitoring techniques may be stated as follows:

Each technique has its strongpoints. The different techniques also focus on different condition statements. This in turn means that no single technique fully serves all requirements at this moment. There is trade-off to be made between complexity and potential of a system. In any case of the examined approaches further development and validation work is required.

Beside the individual RBCM-system characteristics it seems worth noting that preventive monitoring i.e. load monitoring with conventional techniques on single units of a turbine type in various external operating conditions [10] and concerted material R&D work as done in OPTIMAT BLADES is required.
Last but not least the importance of proper design and production processes including powerful quality assurance by NDT-techniques (Non Destructive Testing) is once more confirmed.

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