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Study of the Damage Monitoring System on Wind Turbine Blades

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ABSTRACT

In the light of the world energy crisis in the 1970s and even recently, the only realistic alternative for providing the energy has become renewable energy. In addition, in order to secure the environmental issues, the urge for a clean energy has been a prominent research driver. In this regard, wind energy is known to be one of good candidates and as the demands for wind energy grow, the wind energy industry is moving in the direction of very large-scale designs so that the size of wind turbines has become physically larger, making maintenance and repair works difficult. This study focuses on the safety and maintenance aspect in the design of wind turbine components. Especially, condition monitoring of wind turbine components is of growing importance. In order to improve safety considerations, to minimize down time, to lower the frequency of sudden breakdowns and associated huge maintenance and logistic costs and to provide reliable power generation, the wind turbines must be monitored from time to time to ensure that they are in good condition. Among all the monitoring systems, the structural damage monitoring system is of primary importance because it is the structure that provides the integrity of the system. This study has developed a robust and stable monitoring system of the blade damage by using a piezoelectric film, which is thin, flexible and low cost. Therefore, it can be applied for a variety of industrial area.

1. INTRODUCTION

Development of renewable energy sources has been rapid since the emergence of the world energy crisis into the public arena in the 1970s, and since then the urge for a clean energy to counter the greenhouse effect has been a prominent research driver. Among a variety of renewable energy, the wind turbine business gradually comes to the end because of its technological maturity, good infrastructure and relative cost competitiveness. However, there are still a lot of research works undone in this area. Since the wind turbine providers have developed the large-scale wind turbines in the aspect of higher efficiency and cost-effectiveness, in general, the size of the wind

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turbine has increased over the last several decades. While the large-scale wind turbines have gradually be getting older and older, they reveal variety of problems, defects and damages. For instance, Table 1 shows the some examples of the possible damages in the horizontal axis wind turbine. On the other hand, there are many other problems in the wind turbine business, some of which are as follows,

(1) It is difficult to perform inspection and maintenance work considering the height of the turbine.
(2) When accidents have been reported, some of which have been fatal.
(3) The location of the wind turbine, usually at remote mountainous or rough sea regions, adds even more challenges to the task of maintenance and repair.
(4) For those countries which have poor lifting and handling equipment such as cranes, fork lift, etc but are interested to generate power through wind turbines; the functionality of the turbine system is also a great concern.
(5) The stake becomes higher and higher when the price of the wind turbine increases together with the capacity to become a gigantic expensive structure.
(6) To improve safety considerations, to minimize down time, to lower the frequency of sudden breakdowns and associated huge maintenance and logistic costs and to provide reliable power generation, the wind turbines must be routinely monitored to ensure that they are in good condition (Hameed, 2007).

Table 1 Possible wind turbine damage (Germanischer, 2007)

Assembly	Possible defects
Rotor blade	Surface damage, cracks, structural discontinuities Damage to the lightning protection system
Drive train	Leakages, cracks
Nacelle and force-and moment-transmitting components	Corrosion, cracks
Hydraulic system, pneumatic system	Leakages, corrosion
Tower and foundation	Corrosion, cracks
Safety devices, sensors and breaking systems	Damage, wear
Control system and electrics including transformer station and switchgear	Terminals, fastenings, function, corrosion, dirt

Wind turbine blades can be damaged by moisture absorption, fatigue, wind gusts or lightening strikes. In addition to these climate problems, aerodynamic interaction between different turbines also can cause unpredictable and excessive loads on the blades. These loads accelerate fatigue damage of the blade. In addition, normal aerodynamic loads and loads due to changing gravity moments cause damage of the blades. The blades of modern wind turbine are usually made from fiberglass, which is a cost-effective material for this application. However, because of the low specific modulus of fiberglass, the blade natural frequencies are low and the deflections of the cantilevered blade can be large. For a design lifetime from 10 to 30 year, the blades accumulate a large number of load cycles and fatigue life is an important design consideration and challenger. In the end, these fatigue damage of rotor blades can fail and cause catastrophic damage on a wind turbine. Predicting the exact fatigue life of a blade is difficult, and it is difficult to tell the extent of fatigue damage that might have occurred to a blade. Thus, we aim to propose a method to determine the real-time condition of the rotating blade and warn of possible failure.

In this study, we suggest a damage monitoring system to detect the damage spots before they may merge and propagate to the possible failure of the blade. The blades have sometimes fractures next to the blade root. Buckling of the surface of the blade at the maximum chord section is one of the reasons to make primary failures in the field. The blades usually operate at a large number of cycles under the constant strength and elastic properties so that the fragile fatigue damage propagates quickly to failure. Therefore, the damage monitoring of the rotor blades and temporal identification of potential failure can keep and guarantee the safety of the entire HAWT. Of course, this would also reduce the cost and time during its life time. This is mainly focused on the damage monitoring technique for the condition that the blades are operational or not in service in the field. A condition-based maintenance program using damage monitoring information could minimize the necessary time for inspecting each main component, unnecessary replacement of components so that it prevents failures and improves the availability of power. In addition, damage monitoring can possibly allow the use of lighter blades that would provide higher performance with less conservative margins of safety.

Various existing techniques including visual inspection, C-scan, acoustic emissions and shearography have been suggested to detect the damage in composite blades.(Ness, 1996) However, most of these techniques are labor intensive, inaccurate or difficult to use with. In addition, due to the measurement noise during operation or inaccessibility of the large-scale wind blade it also takes more time. Currently, a number of techniques are still suggested for the damage inside the blade without having to map over the surface of the entire blade.

In this paper, a smart SHM (Structural Health Monitoring) system based on acoustic emission events detection is designed to detect the damage on the surface of blade. Piezoelectric film sensors are used to detect the excitation of the local blade surface because they are flush-installed in situ. This system can detect the excitation on the surface more repeatable than conventional one, and the detection on high frequency excitation can also be reliable. For an empirical knowledge, high frequency excitation is known to be more sensitive to damage than lower frequency excitation such as wind loading. In this study, therefore, the piezoelectric film sensors are used to detect the operational damage.

2. STRUCTURAL DAMAGE

Damage can occur at the most of the wind turbine components; i.e., it can cause a failure in the foundation to the rotating blades, a bolt shears, a load-bearing brace buckles and so on (Ashley, 2007). These structural damages have been reported in many places such as Wales, Scotland, Spain, Germany, France, Denmark, Japan and New Zealand (Rosenbloom, 2006). In Germany, 2002, for example, a blade broke in mid-turn with an audible ‗crack'. In another case, a blade torn-off and flew as far as 8 km and through the window of a house. An extensive documentation of accidents is available at http://www.caithnesswindfarms.co.uk. The possible types of damage that can occur are tabulated, as shown in Table 1.

Hahn(2007) shows, the damage frequency to all the mechanical systems and to the structures is almost equal. Their experience over 15 years is shown in Fig. 1, including failure of both mechanical and electrical components. The failures for mechanical components range from 4% for structural parts/housing and gearbox to 7% for rotor blades. One shows that the break of the blade tip and the damage of yaw bearing are the most frequent damage for a typical wind turbine system. The component failure rate hour is shown in Table 2 (Kahn, 2004).

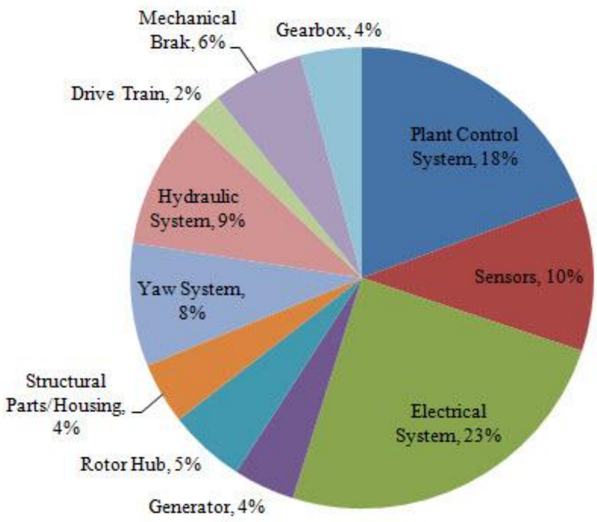

Fig. 1 Unforeseen malfunctions percentage for wind turbines at a wind farm in Germany over 15 years (Hahn, 2007)

Table 2 Component reliability and failure rete h^{-1} (Kahn, 2005)

Component	Failure rates
Tip break	1.000×10^{-4}
Yaw bearing	1.150×10^{-5}
Blades	1.116×10^{-5}
Bolts	1.116×10^{-5}
Hub	1.116×10^{-5}
Generator	0.769×10^{-6}
Gearbox	0.630×10^{-6}
Parking brakes	2.160×10^{-6}
Tower and anchor bolts	1.000×10^{-7}

Although structural damage can be a major cause in any structural component, the most common parts of damage are rotor, blade and tower. Extensive attention has been given to the structural health of blades as they are the key elements of a wind power generation system, and also because the cost of the blades can account for 15~20% of the total turbine cost. It has been shown that the blade damage is the most expensive type of damage to repair and also takes the greatest repairing time. Furthermore, the mass unbalance while the damaged blade is rotating can cause serious secondary damage to the whole wind system if prompt repair action is not taken into account and this can result in the collapse of the whole tower (Rosenbloom, 2006).

In order to understand the blade damage, the anatomy of a blade must primarily be understood. The main elements of a wind turbine blade are shown in Fig. 2 and 3. In addition, Alternative design with spar caps is shown in Fig. 4. The materials of the contemporary blades are usually fibre-reinforced composites with the majority of wind turbine blades being made of glass fibre/epoxy, glass fibre/polyester, wood/epoxy or carbon fibre/epoxy composites (Jureczko, 2005). The use of carbon-fibre-reinforced plastic (CFRP) to manufacture the turbine blade has also increased with increasing rotor size. There is a main spar tube, and the upwind side and downwind side of the blade are constructed and joined together at both the leading edge and the trailing edge using strong adhesive.

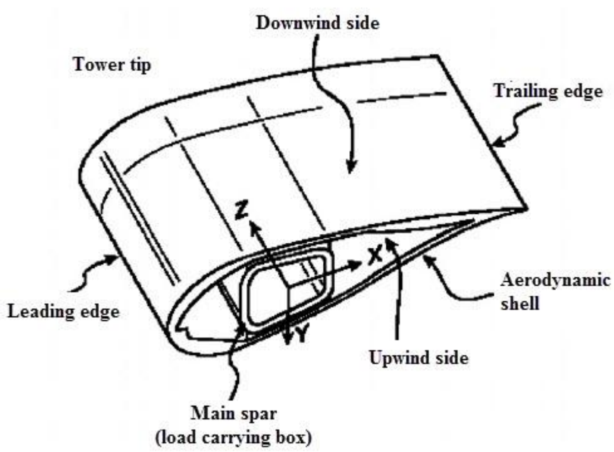

Fig. 2 Main elements of a wind turbine (Sorensen, 2004)

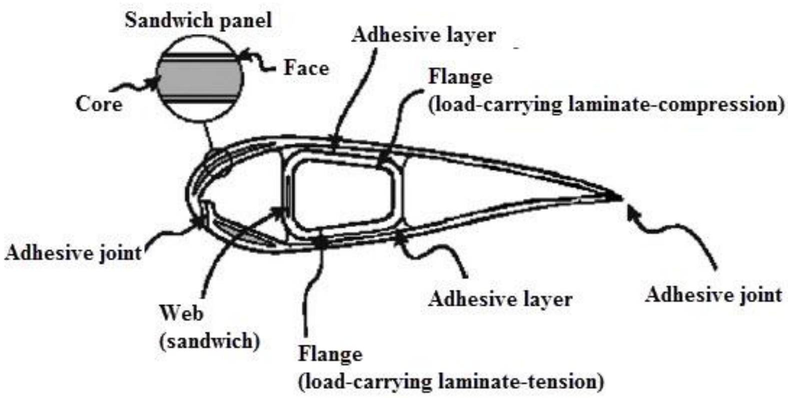

Fig. 3 Nomenclature of the different blade construction elements (Sorensen, 2004)

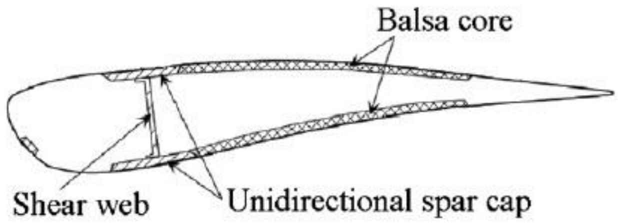

Fig. 4 Cross sectional view of another design of blade with a spar cap

Damage to a blade can occur in various ways. Typical damage in turbine blade is listed in Table 3 and a sketch of the damage types is available in Fig. 5.

Table 3 Typical damage of wind turbines (Sorensen, 2004)

Type	Description
Type 1	Damage formation and growth in the adhesive layer joining skin and main spar flanges(skin/adhesive debonding and/or main spar/adhesive layer debonding)
Type 2	Damage formation and growth in the adhesive layer joining the up-and downwind skins along leading and/or trailing edges (adhesive joint failure between skins)
Type 3	Damage information and growth at the interface between face and core in sandwich panels in skins and main spar web (sandwich panel face/core debonding)
Type 4	Internal damage formation and growth in laminates in skin and/or main spar flanges, under a tensile or compression load (delamination driven by a tensional or a buckling load)
Type 5	Splitting and fracture of separate fibres in laminates of the skin and main spar (fibre failure in tension; laminate failure in comprehension)
Type 6	Buckling of the skin due to damage formation and growth in the bond between skin and main spar under compressive load (skin/adhesive debonding induced by bucking, a specific type 1 case)
Type 7	Formation and growth of cracks in the gel-coat; debonding of the gel-coat from the skin (gel-coat cracking and gel-coat/skin debonding)

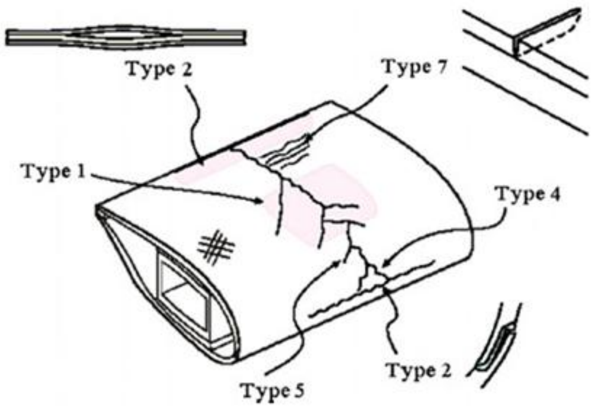

Fig. 5 A sketches illustrating some of the common damage types found on a wind turbine blade (Sorensen, 2004)

There are a lot of reasons to make the wind turbine structural damage. Poor quality control, improper installation and component failure are also responsible for structural damage yielding a collapse of turbines. Lightening can also cause serious structural damage and destroys many towers by causing the blade coatings to peel off, rendering them useless. Fire and strong wind can also damage a wind turbine. One of most critical loads is probably the flapwise (chordwise) bending that arises when the turbine has been brought to a standstill due to high wind, and the blade hits the 50 years extreme gust wind (Thomsen, 2006).

The most dangerous failure is the failure caused by strong wind, which occurs when the braking system fails. The braking system in a turbine is designed to stop the rotors in the event the wind is too strong. When the brakes fail, the turbine spins out of control. In Germany, on numerous occasions during 1999, 2000 and 2003, the brakes on wind turbines failed in high wind, causing the rotor to hit the tower at a strong wind. This resulted in a considerable damage from parts of the blade to the entire nacelle (rotors attached) flying off the tower structure. Blades and other substantial parts have landed as far away as 500 m in typical cases.

3. DAMAGE DETECTION TECHNIQUES

An ideal SHM system typically consists of two major components; a built-in network of sensors for collecting response measurements and a data analysis algorithm/software for interpretation of the measurements in terms of the physical condition of the structures (Rao, 1996). Those methods which are applicable or may have promising application in the near future to the wind turbine system are discussed.

3.1. Acoustic emission events detection method

Processes such as cracking, deformation, debonding, delamination, impacts, crushing and others, all produce localized transient changes in stored elastic energy with a broad spectral content. Acoustic emission (AE) monitoring during loading of wind turbine blades has offered considerable advantages towards the understanding of the complex damage mechanisms which occur on a turbine blade and have enhanced the tester‘s ability to evaluate damage. An AE monitoring of small wind turbine blades certification tests was conducted in Joosse (2002). The test revealed an audible cracking sound from the blade and identified the damage area of failure. Jorgensen (2004) and Wells (1983) used piezoelectric sensors to detect the high-frequency component of the elastic waves (or stress release waves) generated by these energy loss processes within materials and structures. The system can detect much weaker signals in the non-audible frequency domain (20-1200 kHz). Beattie (1997) shows that fatigue tests of large fibre-reinforced plastic wind turbine blades can also be monitored by AE techniques. The AE signals can be characterized in terms of amplitude and energy and inferences can be made about the kinds of damage processes taking place in the blade. The AE event will cluster around a certain point at a loaded structure and eventually the structure failed at that particular location of the failure points or damage locations. This method can also be used to determine damage criticality.

The characteristics of an AE event which cluster around a potential failure point and the increase of intensity as damage becomes more critical, can be utilized by pattern recognition software to evaluate the damage. This pattern recognition software has the potential for application to various similar wind turbine blade designs. The consistency in the presence of a distinguishable family of AE data immediately prior to failure also enables the assessment of the blade‘s ability to withstand specific loads.

In cases where high accuracy of damage evaluation is needed, the number of sensors must be increased and subsequently the number of data output to the signal processing system also increased. In order to reduce the number of data, a structural neural system (SNS) is proposed for damage monitoring system. A highly distributed continuous sensor concept, that mimics the signal processing in the biological neural system, is adopted. The continuous sensors for SNS are formed by individual piezoelectric sensors connected in a series, as illustrated in Fig. 6. Each of the small squares indicates two adjacent sensor nodes, as shown in the magnified view on the right of Fig. 6. The row continuous sensors are connected to an analogue processor and the column continuous sensors are connected to another analogue processor. The analogue processors will simplify the data and send only two outputs each to the computer, which greatly reduce both the number of data to be processed and the computer power. The proposed in-service SNS method can detect the AE produced by cracking, delamination, bearing damage, rotor imbalance, flow instabilities, impacts or other material failure modes. It was proved in some experiments that the method can detect damage early and track the AE event during the damage growth in a wind turbine blade.

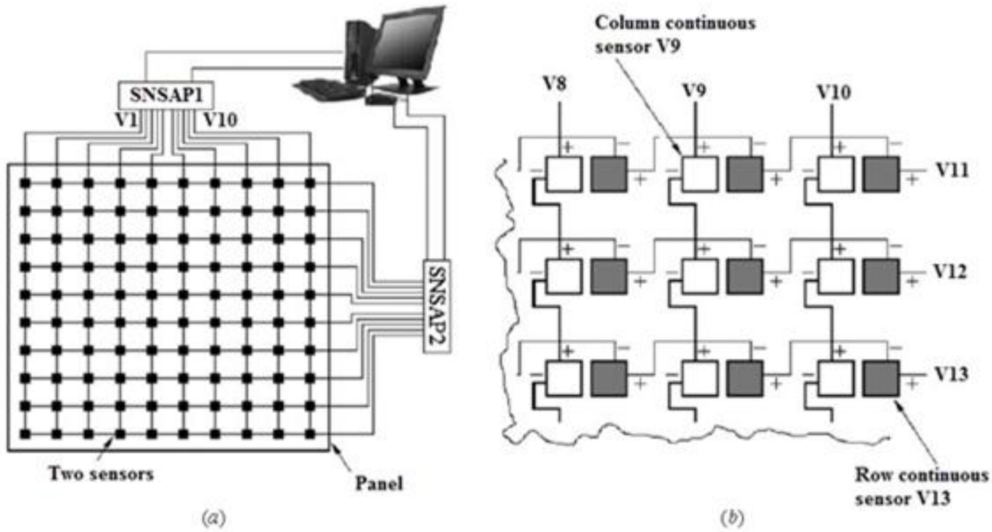

Fig. 6 Architecture of the SNS proposed in Schulz (2006); (a) each small square indicates two adjacent sensor nodes. In this example, there are ten row continuous sensors and ten column continuous sensors; (b) the magnified view at the right shows the detail of sensors arrangement to form row continuous sensors and column continuous sensors.

The most common sensor type used in monitoring stress waves in materials is based on a surface-mounted piezoelectric crystal. However, there are many other sensors that exist which either use alternative methods for detecting stress wave activity or use piezoelectric materials in different ways, such as thin film sensors, piezoelectric composite materials, rolling sensors, embedded piezoelectric sensors and optic based sensors (Lading, 2002).

3.2. Ultrasonic methods

Ultrasound is a well-established method for investigating the inner structures of solid objects. Ultrasonic scanning is also very useful for investigating composite structures. The basic principle of the technique is that an ultrasonic wave is passed through the material and is then reflected and/or mode converted by defect. A transmitter transfers ultrasound waves into the material and the signal from this is picked up by a receiver once it has passed through the material. In the simplest arrangement, the transmitter and receiver are placed on opposite surfaces of the material. The technique may also be applied with a single transmitter/receiver transducer in a pulse-echo mode or with separate transmitter and receiver transducers placed on the same side of the material (Lading, 2002).

Ultrasound probing will typically reveal planar cracks oriented perpendicular to the direction of sound wave propagation (Sorensen, 2002). The transmit time and/or amplitude of the ultrasound is usually monitored. The transit time can be used to determine the position of the defect relative to the position of the transducers while the amplitude can be used assess the severity of the defect (Lading, 2002). In addition, the damage of less than a few millimeters can also be detected.

Ultrasonic testing has proved its effectiveness in a variety of applications for example, inspection of adhesively bonded multilayered structures, laminated composite components, including detection of delaminations and interlaminar weakness (Tuzzeo, 2001). In the case of adhesively bonded multilayered structures, relatively limited success has been obtained with the ultrasonic technique. It is suitable for detecting delamination and cracks in adhesive that are oriented at right angles to an ultrasonic wave propagation, impact damage, voids and porosity.

Acoustic wavefield imaging (AWI) is another variation of the ultrasonic method. (Michaels and Michaels, 2006) used a sparse array of permanently mounted piezoelectric transducers to generate acoustic waves which propagate through a structure. An external air-coupled transducer acts as a receiver and is scanned over the surface of the specimen. Ultrasonic waveforms are recorded from each location of the pixel grid for the AWI image and then stored waveforms are processed and displayed as consecutive time slice, as shown Fig. 7. Propagating waves are visible as a concentric wavefield emerging from the embedded source transducer. Interactions with discontinuities in the structure are visible as scattered waves (Michaels, 2006).

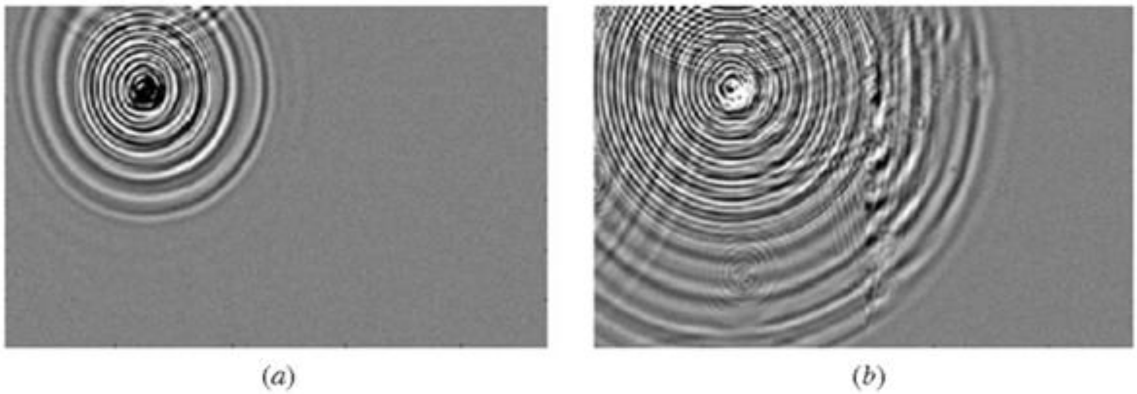

Fig. 7 Acoustic wavefield images at different propagation times. Wave interactions with both boundaries of the plate and impedance discontinuities in the specimen are clearly visible on these AWI snapshots

The transducer pair for AWI can be composed of a laser ultrasonic generator and a laser interferometric sensor (Sohn, 2003). Alternatively, if a structure already contains ultrasonic transducers under the built-in damage monitoring system scheme, either a laser ultrasonic generator or receiver can be used to realize the ultrasonic pitch-catch (Lee, 2007). If the built-in transducer is used as an ultrasonic transmitter, the laser interferometric sensor, air-coupled transducer electromagnetic acoustic transducer (EMAT) or contact transducer can be used as the scanning sensor for AWI. Since the ultrasonic wavefield imaging technology provides a scanned movie or snapshots, it can provide easy explanations on the wave propagation mechanism and the interaction of the wavefield with structural damage (Lee, 2007).

3.3. Modal-based approach

Modal-based methods are among the most common damage detection methods used, principally because they are simple to implement on any size structure. Structures can be excited by ambient energy (Siringoringo, 2006), an external shaker or embedded actuators and embedded strain gauges, piezoceramics or accelerometers can be used to monitor the structural dynamic response (Kessler, 2002). The basic idea behind this technology is that modal parameters, notably frequencies, mode shapes and modal damping, are functions of the physical properties of the structure (mass, damping and stiffness). Therefore, changes in the physical properties, such as reductions in stiffness resulting from the onset of cracks or loosing of a connection, will cause detectable changes in the modal properties (Gross, 1999). Structural damage detection is based on a comparison between the response from a ‗predamage' state and that from a ‗post-damage' state (Gross, 1999). Since changes in modal properties, or properties derived from these quantities, are being used as indicators of damage, the process of modal-based damage detection eventually reduces to some form of pattern recognition problem (Doebling, 1998).

Sundaresan (2002) and Ghoshal (2000) reported the use of piezoelectric patches at hot spots to compare the resonant frequency. In this approach, the exciting actuator is located at the center of a symmetric region so that localized symmetrical properties of the structure can be exploited to minimize the need for pre-damage data and to compensate for changes in the structure not related to damage. Damage is determined using the differences in the response at the resonances of the healthy and damaged structure.

Ambient excitation can also be used and is more attractive since it allows modal analysis to be performed under service condition of the structures and does not require any artificial exciters (Siringoringo, 2006).

There is another type of modal-based damage detection method called resistance-based damage detection method. It is a unique modal-based approach because it is capable of detecting local damage. It has been developed by utilizing the electromechanical coupling property of piezoelectric materials. The basic concept of this approach is to monitor the variations in the electrical impedance of piezoelectric material, which is directly related to the mechanical impedance of the host structure and will be affected by the presence of structural damage. According to Park (2003), when a piezoelectric patch attached to a structure is driven by a fixed alternating electric field, a small deformation is produced in the piezoelectric wafer and the attached structure. The dynamic response of the structure to the mechanical vibration is transferred back to the piezoelectric wafer in the form of an electrical response. Only local response of the structure will be transmitted to the sensor if the frequency of the excitation is high enough. When a crack or damage causes the mechanical dynamic response to change, it is manifested in the electrical response of the piezoelectric wafer. Through monitoring the measured electrical impedance and comparing it to a baseline measurement, one can qualitatively determine that structural damage has occurred or is imminent.

The localized nature of the sensing region provides an advantage in that the impedance sensor is less sensitive to boundary condition changes or any operational vibrations, which usually affect lower order global modes (Peairs, 2004). This method has been shown to be effective in detecting damage in various structures including composite structures (Peairs, 2004). A wireless damage monitoring system was also demonstrated to sense the loosening of bolt joint for an aluminum structure. (Pitchford, 2007) used this method to detect damage on a wind turbine blade. They introduced damage in a controlled way by adding mass and clamping as well as actual damage at various locations of interest on the blade section. Their results show that impedance-based damage monitoring system was able to detect damage on the blade section and it seems that this damage monitoring system method is a promising method to use on blades either in critical locations or in conjunction with other damage monitoring system methods which both utilized the same piezoelectric patches.

The digital image correlation technique can be adapted as a modal-based method for wind turbine too. This method utilizes a digital video camcorder to capture the video of an area of interest on the target structure. The area of interest is patched with pattern of white spots on a black background. A digital image correlation algorithm is then used to compare the video frames of the frames of the pattern with a baseline image. The displacement of the area of interest can be obtained in real time and the global structural integrity can be known using model analysis. This method has been applied to flexible bridges to determine their dynamic displacement and natural frequency. The result showed that it is comparable to the resolution of a laser vibrometer but much more cost effective. A 3D version of this method is also available but its effectiveness as in situ structural damage monitoring of wind turbine is yet to be validated.

4. DESIGN OF DAMAGE DETECTION SYSTEM

4.1. The structural neural system (SNS)

Identification of anomalies in the response of a structure is very important to prevent catastrophic failures. In a long-term continuous monitoring system, these anomalies often appear as transient abrupt changes hidden in measurement data (Moyo, 2002). The SNS can monitor complicated parts of a structure by listening for an energy release due to damage. The SNS analog processor has "n" channels of input from the sensors and only two channels of output. Fig. 8 shows the analogy of an aircraft with the SNS. The aircraft has sensors attached to the inner surface for continuous health monitoring. These sensors are connected to form the SNS that is in-turn connected to the SNS analog processor (not shown in this figure) and then to the computer for data acquisition, storage and analysis. The SNS mimics the architecture of the human biological neural system.

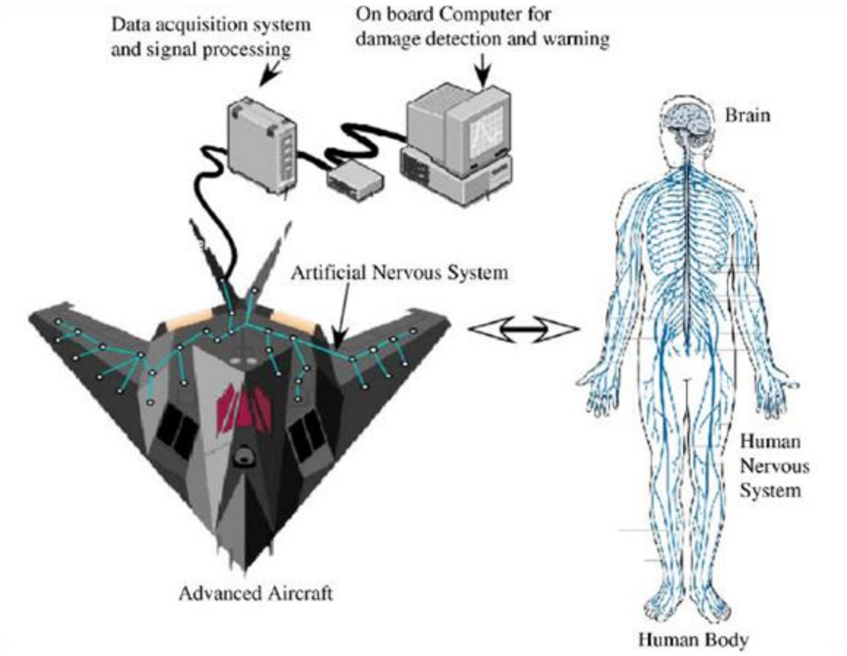

Fig. 8 Aircraft and biological neural systems

The SNS reduces the required number of data acquisition channels to monitor the health of the structure. One of the output channels predicts the location of the AE and the other channel captures the combined time domain signals caused by straining of the sensor due to the AE. The combined time domain signal indicates the frequency content of the AE. The outputs from the SNS analog processor are input to a computer for data acquisition. Note that this system has several advantages because most of the signal processing is done in an analog fashion. This reduces the cost of maintaining and obtaining large number of digital data acquisition channels. The SNS can be constructed using sensors connected in series that are connected to electronic logic circuits.

4.2. Remote monitoring

The diagram in Fig. 9 shows a structure architecture possible using Can-bus line with distributed embedded module linked with in and running piezoelectric film sensors attached to the blade structure. The information is relayed along the Can-bus line and transmitted to a remote computer.

It has been assumed here that the modules and transmitters are distributed along the blade. Placed together, these components are not large and so this is easily possible. The distributed design reduces cable lengths and the likehood of total loss of function in the event of an accident.

One of the major strengths of such a system is that the remote computer system can also communicate with the modules. This means the function of the module can be changed "on-line" by an operator back in the office.

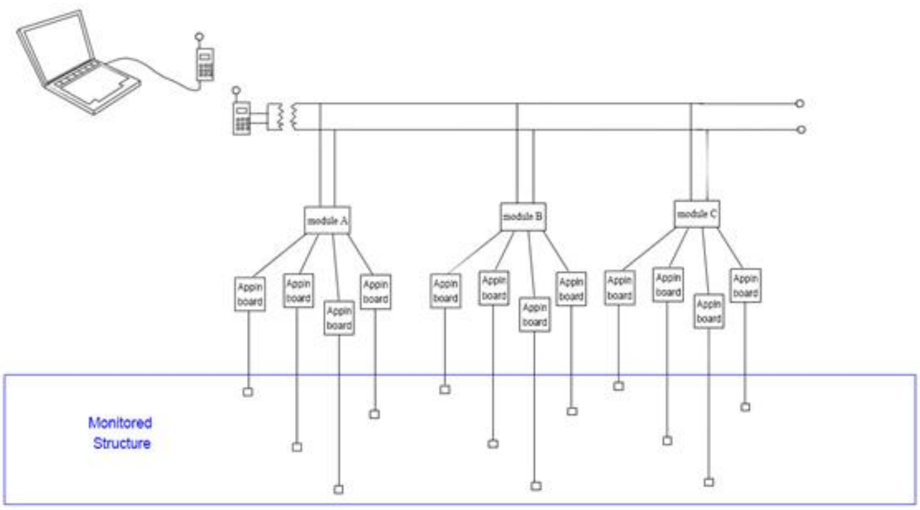

Fig. 9 A generalized Can-bus system schematic for remote monitoring of a structure

4.3. Fabrication issues and sensor distribution

Installing a sensor network within a mass produced structure such as wind turbine blade will involve some degree of additional work during the fabrication process. Ideally this ‗extra' work will be minimized. The blades consist of two large shells and an internal arrangement of stiffening beams and stringers. It can be proposed that the Can-bus line and modules are mounted on the internal spar and the sensors arranged so that they can be attached and tested during an additional stage of fabrication before the two shells are closed. It is impossible to determine whether this would in fact be a suitable method or not without more detailed information about the scope of the monitoring system and the specific hardware involved.

Throughout this design we assumed a 40 m standard blade length. A piezoelectric film sensor resonant at 150 kHz will only have a sensory range of 0.7 - 1.0 m when detecting the micro-cracking in composites that are the precursors to delaminations, cracking and other visible/repairable damage. Sensor spacing greater than 2 m will therefore leave areas where such micro-cracking damage would not be detected.

We can illustrate the effect of sensor detection range on sensors numbers required in the following simple way. For point sensors, two key parameters are the maximum allowable undetected damage size, *D* and the sensory range, i.e., the radius, *R*, of the area(assumed to be circular in-plane) in which the sensor detects damage. Assuming all sensors placed in a single row along the entire blade length, *L*, the number of sensors required is:

$$N = \frac{L - D}{2R + D} \tag{1}$$

Fig. 10 shows N calculated as a function of the undetected damage size for two value of the sensory range and L=40 m. it is seen that the number of sensors required depends strongly on both R and D.

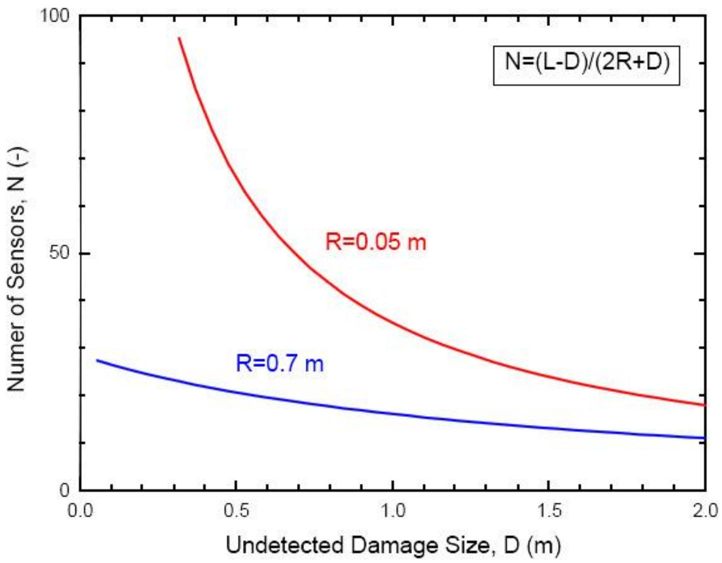

Fig. 10 Number sensors required a 40 m long wind turbine blade as a function of undetectable damage size for two different sensory ranges

A sensor spacing less than 2 m would result in complete blade coverage in a zonal sensor array, but in order to obtain the high accuracy (1 cm) source location possible using time of flight measurements in a planer location array, every point on the blade must be no further than 1 m away from 3 sensors. It is obvious, therefore, that to ensure complete coverage of such a huge structure a very large number of sensors would be required and thus is a problem that must be addressed.

One reasonable solution to this problem is to restrict the monitored area to a specific part of the blade and so reduce the number of sensors required. It might be decided, for example, to only have sensors along the trailing edge, or along the central spar, or around the blade root, or at the mid-blade area, and so on.

Another solution that may prove to be satisfactory is to restrict the number of sensors to a set number. These sensors are then ‗zoned' along the length of the blade. A profile of the stress wave activity along the blade can be produced that may be very useful in speeding up scheduled blade inspections, but it is accepted that some areas of the blade are not being covered by the monitoring system.

5. CONCLUSIONS

Main concept of damage monitoring system is acoustic emission events detection method (AE) and the structural neural system (SNS). The concept for the smart blade is shown in Fig. 11. AE events detection method is very powerful in detecting any damage mode up to micro-scale. However, this method is less capable in damage characterization and further damage evaluation if a suitable. For real-time structural damage monitoring, damage localization based on wave speed in complex structures may not be the most effective method because the wave speed in a structure is a function of the geometric and material parameters of the structure. An example of different strategies that can be implemented to improve the damage evaluation capability of AE events detection method is the in-service structural neural system (SNS). The proposed passive SNS has high sensitivity to damage and simple instrumentation ad wiring of the monitoring system. Most of the signal processing is done in an analogue fashion, which can reduce the cost of maintaining and obtaining a large number of digital data acquisition channels. As suggested by this paper, the SNS strategy is also possible for application in the fabrication of smart turbine blades, where the piezoelectric nerves can be self-powered and the active fibre composite material can also be used for micro power generation to power the embedded signal conditioning and data acquisition/analysis system. Wireless transmission of the reduced condition information could simplify the Structural Damage Monitoring system.

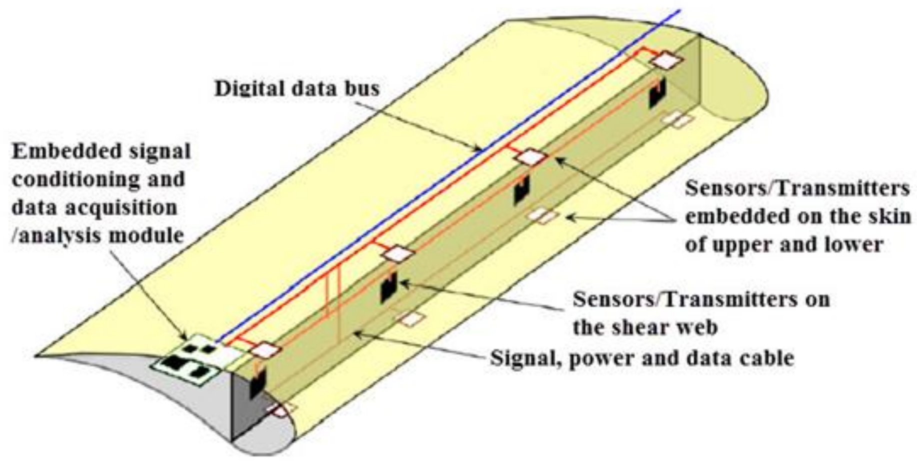

Fig. 11 Conceptual design of a smart wind turbine blade using SNS as the Structural Damage Monitoring system

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