A review of NDT techniques for wind turbines

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Wind machines and traditional 'Dutch' windmills preceded electricity supply and were used for grinding grain. They were always attended, sometimes inhabited and, largely, manually controlled. They were integrated within the community, designed for frequent replacement of certain components and efficiency was of little importance. Wind turbines have been in use since 1941. The function of a modern power-generating wind turbine is to generate high quality, network frequency electricity. There is information and advice on the non-destructive testing (NDT) of wind turbines in Europe and internationally, but because mass production of wind turbines is fairly new, no manufacturing standards have been set yet. There is also a need for European standards, in the testing, certification and accreditation of turbines and components.

The main objectives in this paper are to review the current state of NDT of wind turbines at manufacture and in-service, and to establish the most promising NDT methods for detecting flaws of most concern.

1. Introduction

Historically, wind machines were used for grinding grain in Persia as early as 200 BC. Wind turbines have been in use since 1941 when the world's first megawatt-size wind turbine was connected to the local electrical distribution system in Vermont, USA. The function of a modern power-generating wind turbine is to generate high quality, network frequency electricity. To give an example of the scale of the industry today, there are over 35,000 wind turbines worldwide and the UK has 40% of Europe's wind resource.

The main aim of this paper is to provide a review of the current state of NDT of wind turbines, based on published evidence, at the time of manufacture and at the time of periodic inspection.

Whilst it is well known that Acoustic Emission (AE) is successful in detecting and monitoring flaws in wind turbines, it is not strictly an NDT method. Nevertheless it is considered in this review.

2. Manufacturers

Germany, Spain and Denmark accounted for almost 80% of the wind power capacity installed in Europe in 2003[1]. Germany continues to be the leader in terms of cumulative and annual megawatt (MW) wind turbines installed. There has also been a huge growth in the Spanish market in recent years but Denmark continues to dominate the manufacturing side of the industry worldwide.

Nine of the top ten turbine manufacturers are European and wind energy is an outstanding European success story, with European companies manufacturing more than 90% of the turbines sold worldwide in 2002.

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3. Types of wind turbines

Wind turbines can be separated into two general types based on the axis about which the turbine rotates. Turbines that rotate around a horizontal axis are most common. Vertical axis turbines are less frequently used. Wind turbines can also be classified by the location in which they are to be used. There are onshore and offshore wind turbines.

3.1 Horizontal axis

Horizontal Axis Wind Turbines (HAWT) have the main rotor shaft and generator at the top of a tower, and must be pointed into the wind by some means. Small turbines are pointed into the wind by a simple wind vane, while large turbines generally use a wind sensor coupled with a servomotor. Most have a gearbox too, which turns the slow rotation of the blades into a quicker rotation that is more suitable for generating electricity.

3.2 Offshore

The fact that water has less surface roughness than land means the average wind speed is usually higher over open water. This allows offshore turbines to use relatively shorter towers above the water surface, making them less visible.

The offshore environment is, however, more expensive compared to onshore for the following reasons:

- Offshore towers are generally taller when the submerged height is also included.
- Offshore foundations are more difficult and more expensive to build.
- Power transmission is through undersea cable, which is more expensive to install.
- The offshore environment is also corrosive and abrasive.
- Repairs and maintenance are much more difficult.
- Offshore wind turbines are outfitted with extensive corrosion protection measures like coatings and cathodic protection.
- The stresses on offshore wind turbine towers are also greater due to tidal stress.

4. Turbine design and construction

Most wind turbines have upwind rotors that are actively yawed to preserve alignment with wind direction. The three-bladed rotor is the most popular and, typically, has a separate front bearing with a low speed shaft connected to a gearbox which provides an output speed suitable for a four-pole generator (see Figure 1). Commonly, with the largest wind turbines, the blade pitch will be varied continuously under active control to regulate power at the higher operational wind speeds (furling). Support structures are most commonly tubular steel towers tapering in some way, both in metal wall thickness and in diameter from tower base to tower top. Epoxy-based resin systems dominate the market in blade manufacture and carbon fibre reinforcement is increasingly used in big blades.

In 2006, the focus of attention is on technology around and above the 2 MW rating and commercial turbines now exist with heights over 100 m and rotor diameters up to 100 m. Designs with *variable pitch* and *variable speed* dominate the market while *direct drive* generators are becoming more prevalent.

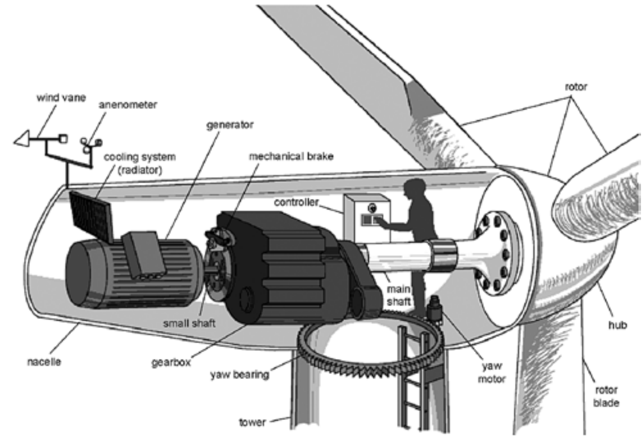

Figure 1. Wind turbine open nacelle (from Danish Wind Industry Association)

5. Flaws and NDT at manufacture

Because mass production of wind turbines is fairly new, no manufacturing standards have been set yet. Efforts are now being made in this area on the part of both the government and manufacturers.

While wind turbines on duty are relied on to work 90 percent of the time, many structural flaws are still encountered, particularly with the blades. Cracks sometimes appear soon after manufacture. Mechanical failure, due to alignment and assembly errors, is common. Electrical sensors frequently fail because of power surges. Non-hydraulic brakes tend to be reliable, but hydraulic braking systems often cause problems.

5.1 Manufacturing flaws on turbine blades

Manufacturing flaws can cause problems during normal operation. For example, blades can develop cracks at the edges, near the hub or at the tips (Figure 2). Fibreglass rotor blades are regarded as the most vulnerable components of a wind turbine(2).

Typical manufacturing flaws on the blades may be summarised as delaminations (Figure 3), adhesive flaws and resin-poor areas. Here are some specific flaws at particular locations:

- ❑ Skin/adhesive: this is bad cohesion between the skin laminate and the epoxy or the epoxy is missing.
- ❑ Adhesive/main spar: this is when there is no cohesion between the adhesive and the main spar.
- ❑ Delamination in main spar laminate.
- ❑ High damping in skin or main spar laminate, which could be caused by porosities or change of thickness of laminate.

5.2 Manufacturing flaws on the tower

A tubular tower is made of a lot of sheets of iron that are welded together. A flange is welded onto each end of the sections. The welding is checked thoroughly using ultrasonic NDT.

5.3 NDT techniques at manufacture

5.3.1 Visual inspection

Relatively advanced NDT testing methods are used to examine rotor blades. The methods employed include penetrant testing and visual inspection with the use of miniature cameras or endoscopes.

At present, it appears that mechanical components aren't tested at manufacture but the cause of their damage can be determined. For example, endoscopes are used for the visual inspection of planetary gear transmissions. However, damaged components are usually examined in a materials laboratory.

5.3.2 Ultrasonic NDT

An ultrasonic test can be carried out to investigate if any damage is present in the wind turbine blade. Ultrasonic inspection reveals these flaws quickly, reliably and effectively and is the most often used non-destructive composite inspection method in industry. The main advantage of ultrasound scanning is that it enables us to see beneath the surface and check the laminate for dry glass fibre and delamination.

5.3.3 Tap test

The tap test can be used to verify some of the results from the ultrasonic test and it is also a good method to discover irregularities in the structure. The method is based on the fact that the sound emitted when knocking on the structure changes when the thickness or material type changes or when porosities are present. It could also be caused when there is a disbond between the skin laminate and the main spar. There are three types of tap testing equipment; a manual tapping hammer, the 'Woodpecker' portable bondtester and the Computer Aided Tap Tester (CATT) system.

All the automated tap methods have the advantage that they can produce a print of the damaged area, which is both useful and a permanent record of the damage found. All the tapping methods work well for thin laminates, honeycomb structures and other sandwich panels but are not so effective on thicker parts.

5.3.4 Infrared thermography

The adhesive joints are critical points in the blade structure. That is why they are inspected with particular care. Infrared (IR) scanners are used to examine the blade throughout its length, measuring exactly the same points each time. The scanner is able to see through the laminate and check the adhesive joint. It records temperature differences in the adhesive, possibly identifying flaws, and takes a series of pictures. If there are any doubts, a point can be highlighted and later analysed using electronic image processing. If flaws are found, they can almost always be repaired immediately.

6. Flaws and NDT in-service

As the force of the wind is so irregular, the driving mechanism of a wind turbine is subject to much greater dynamic loads. Virtually

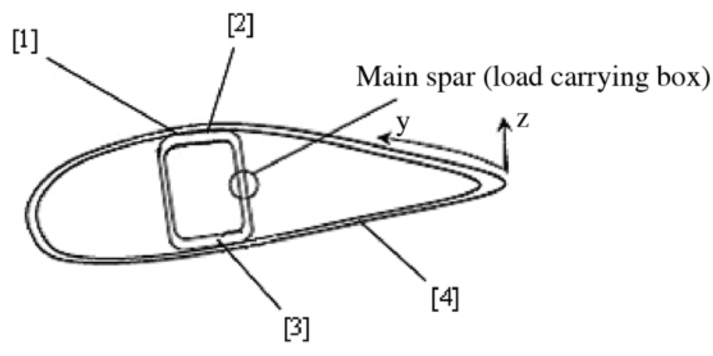

Figure 2. Sketch of section of blade (local coordinates) Risø

Figure 3. Delamination of the blades

all components of a wind turbine are subject to damage, including everything from the rotor blades to the generator, transformer, nacelle, tower and foundation.

Wind turbines do have regular maintenance schedules in order to minimise failure. They undergo inspection every three months, and every six months a major maintenance check-up is scheduled. This usually involves lubricating the moving parts and checking the oil level in the gearbox. It is also possible for a worker to test the electrical system on site and note any problems with the generator or hook-ups.

6.1 Flaws on turbine blades

In-service flaws have been identified in the following report:

Risø-R-1391(EN) 'Identification of Damage Types in Wind Turbine Blades Tested to Failure' Christian P. Debel, AFM. ISBN 87-550-3178-1; ISBN 87-550-3180-3 (Internet) ISSN 0106-2840.

6.2 Flaws on the tower

For wind turbine towers, wind load is regarded as the main load. The analysis of damage in most towers shows that it occurs under a wind of medium intensity, and the reason is fatigue failures (Figure 4). The number of sections which are dangerous from the point of view of fatigue is determined during the design of the structure.

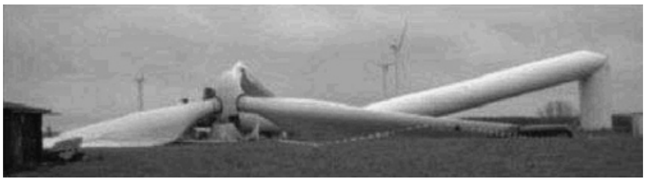

Figure 4. Collapsed wind turbine tower due to fatigue cracks and wind loading combination

6.3 Flaws on rotor bearings

Cyclic stresses fatigue the blade, axle and bearing material, and were a major cause of turbine failure for many years. When the turbine turns to face the wind, the rotating blades act like a gyroscope. As it pivots, gyroscopic precession tries to twist the turbine into a forward or backward somersault. For each blade on a wind generator's turbine, precessive force is at a minimum when the blade is horizontal and at a maximum when the blade is vertical. This cyclic twisting can quickly fatigue and crack the blade roots, hub and axle of the turbine.

Spalling (breaking up into fragments) of rotor shaft bearings can result in cracked rings, and in some cases, revolution of the inner rings around the shaft causes cracks in the shaft that can result in a total loss of the turbine. Figure 5 illustrates what can happen when the rotor bearings fail (in this case the blades landed 1 km away after having crossed a road)

6.4 Flaws on transmission bearings

The raceways of the roller bearings (usually self-aligning roller bearings) of the low-speed shaft can develop spalling over the entire circumference of the raceway, and excessively high temperatures can damage the bearings of the high-speed shaft. Raceway damage can negatively affect the transmission of forces to gears.

6.5 Flaws on gears

Frequently, scuffing along the line of action as well as unsatisfactory tooth contact patterns are encountered. Highly loaded conditions result in chipping or micropitting.

6.6 Flaws on generator bearings

Generator bearing slippage and wear can ultimately cause inner rings to rotate around the shaft to the point that rotor makes metal-to-metal contact.

Figure 5. The loss of the turbine due to rotor bearing flaws

6.7 Flaws on electrical components

Flaws in the electrical system can also result in the outage of a wind turbine. Often damaged generator windings, short-circuit and over-voltage damage to controllers and electronic components as well as damage to transformers and wiring are found.

6.8 NDT techniques in-service

There are not that many NDT techniques used in-service, but it is well known that AE is able to locate and monitor both high damage regions and flaws in the blade structure.

7. Published results from research studies in NDT

7.1 Acoustic emission

A substantial amount of work has gone on in AE since 1993[3]. A fatigue test of a wind turbine blade which was conducted at the National Renewable Energy Laboratory shows that fatigue tests of large FRP wind turbine blades can be monitored by AE techniques and that the monitoring can produce useful information[4]. AE testing procedures, developed during a laboratory blade testing programme, have been applied to an in-service wind turbine blade in 2003[5]. In the Framework of the Non-Nuclear Energy Programme, JOULE III from 1998 to 2002[6], the partners successfully developed a methodology for the structural integrity assessment of wind turbine blades, either in-service, or during certification testing, based on Acoustic Emission monitoring during static or fatigue loading. Within the framework of JOULE III, specialised pattern recognition software for AE data analysis and wind turbine automatic structural integrity assessment has been developed.

7.2 Full scale testing of wind turbine blade to failure

A 25 m wind turbine blade was tested to failure when subjected to a flapwise load[7]. With the test setup, it was possible to test the blade to failure at three different locations. The objective of these tests is to learn about how a wind turbine blade fails when exposed to a large flapwise load and how failures propagate. The report also shows results from the ultrasonic scanning of the surface of the blade and it is seen to be very useful for the detection of flaws, especially in the layer between the skin laminate and the load carrying main spar. AE was successfully used as sensor for the detection of damages in the blade during the test.

7.3 Wireless detection of internal delamination cracks in CFRP

In this study, a wireless system using a tiny oscillation circuit for detecting delamination of carbon/epoxy composites is proposed[8]. A tiny oscillation circuit is attached to the composite component. When delamination of the component occurs, electrical resistance changes, which causes a change in the oscillating frequency of the circuit. Since this system uses the composite structure itself as a sensor and the oscillating circuit is very small, it is applicable to rotating components. The wireless method is found to successfully detect embedded delamination, and to estimate the size of the delamination.

7.4 Structural health monitoring techniques for wind turbine blades

These experiments indicate the feasibility of using piezoceramic patches for excitation and a Scanning Laser Doppler Vibrometer or piezoceramic patches to measure vibration to detect damage[9].

Further testing of different smaller damages and types of damage is needed to verify the sensitivity of the methods. The resonant comparison method can be used for operational damage detection while the operational deflection shape method produces non-symmetric contours that are an easily interpretable way to detect damage in a structure that is not moving.

7.5 Infrared thermography for condition monitoring of composite wind turbine blades

Infrared thermography has the potential for providing full-field non-contacting techniques for the inspection of wind turbine blades[10]. For application to turbine blades, the sensitivity of the thermal imaging has been shown to be suitable for non-destructive examination during fatigue testing; furthermore, it is thought that for blades *in situ*, the wind loading conditions may be sufficient to create effects detectable by thermal imaging.

8. Standards

Project certification can be done to a degree under the International Electrotechnical Commission (IEC)-CAP standard. However, the CAP standard is not sufficient as it stands. High quality and efficient standardisation and certification are vital given the number of turbine types. Standards designed for one market segment can be inappropriate in another, and standards across the segments should normally be limited to essential operating and safety standards.

The standards that are perceived to be lacking in some way need to be identified and appropriate actions for new standards and background research initiated. There is also the need to develop turbine type categories on the basis of ISO/IEC and CEN/Cenelec standards.

8.1 At manufacture

At the time of manufacture, the inspection standards should be designed for detecting manufacturing flaws (which are often quite different from in-service flaws) and to ensure that the wind turbines are manufactured correctly.

8.2 International standards activities

The American Wind Energy Association (AWEA) is the recognised US industry organisation for standards development. AWEA maintains contact with the IEC standards development activities through the involvement of staff members and industry representatives on TC-88 standards subcommittees.

There are at present published standards on the safety requirements for large wind turbines, small wind turbine systems, acoustic emission measurement techniques and performance measurement techniques (see also www.ansi.org).

8.3 European standards

The current state of European standards in relation to wind turbines is summarised in Table 1.

Table 1. European standards

Project number	Standard reference	Technical body	Title (EN)	Directive
7125	EN 61400-2:1996	CLC/TC 88	Wind turbine generator systems – Part 2: Safety of small wind turbines	73/23/EEC
12538	EN 61400-1:2004	CLC/TC 88	Wind turbine generator systems – Part 1: Safety requirements	73/23/EEC
16198	prEN 61400-2:2005	CLC/TC 88	Wind turbine – Part 2: Design requirements for small wind turbines	73/23/EEC
11914	EN 50308:2004	CLC/TC 88	Wind turbines – Protective measures – Requirements for design, operation and maintenance	98/37/EC Pending

9. Conclusions

There is a need to develop:

- European standards for use by developers, investors and insurance companies on risk, economic viability, performance, reliability, and owners and managers of wind farms.
- European certification and accreditation systems for components, turbines and projects, including standards for the NDT of components and turbines, particularly for in-service NDT.

10. Acknowledgements

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