Reliable Automated NDT of Wind Rotor Blades

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Abstract
The paper discusses a range of automated ultrasonic non-destructive testing solutions for reliable inspection of the wind rotor blade throughout its lifetime. Different aspects of automated ultrasonic inspection are discussed addressing quality improvements related to the design, the manufacturing and the operation of wind rotor blades. In the design phase of blades a detailed automated ultrasonic inspection of pre-production blades gives valuable information on the complicated blade layup. Results from test blocks with artificial flaws demonstrating interface issues, laminar flaws, as well as monitoring of unidirectional fibre waviness (wrinkles) is addressed with the latest automated array technology. In the production phase of blades, the inspection time is a dominant factor. Scanning strategies for automated ultrasonic systems to scan large wind rotor blades are compared in terms of speed and complexity. During blade operation, the actual structural condition has to be checked periodically, avoiding valuable downtime. Various smart platforms and blade-guided robot systems are compared. Moreover, unique blade crawling robots are currently developed for remotely controlled NDT inspection on vertical blade surfaces - on-shore as well as off-shore.

Keywords: Material characterization, automated ultrasonic testing, wind rotor blades, fibre reinforced composite, intelligent phased array probes, reliable inspection, inspection time, scanning strategies, access, wrinkles.

1. Introduction
The quality of glass- and carbon fibre reinforced composite structures in wind rotor blades is an important topic for both manufacturers and turbine operators. However, quality assessments of rotor blades is a challenge for the entire wind community due to lack of standards, increasing complexity of large rotor blades, poor inspect ability and a demand for a more cost effective production. The most commonly applied non-destructive testing (NDT) technique for composite structures is ultrasonic inspection due to the high sensitivity to the defects commonly found in spar caps (girders) and web bonding. However, other techniques, mainly optical and thermal techniques, have been developed to address specific problems. The most popular are X-ray imaging, shearography, terahertz and active thermography [1-2]. The drawback of these methods is there limited depth penetration and that these methods are still considerably more expensive to automate than conventional ultrasonic methods. The aim of this work is to discuss a range of automated ultrasonic testing (AUT) solutions for reliable inspection of the wind rotor blade throughout its lifetime. Different aspects of automated inspection are discussed addressing quality improvements related to the design, the manufacturing and the operation of wind rotor blades.

2. Reliable AUT in the blade design phase
Automated ultrasonic scanners may be helpful in the design phase of wind rotor blades. Sub components of glass reinforced plastic (GRP) and carbon fibre reinforced plastic (CFRP) may be scanned to demonstrate elastic material properties and larger subcomponents can be inspected to examine the interaction of different materials. However, due to the composition of composites the subcomponent materials are strongly anisotropic and measurements of ultrasonic phase velocity in predetermined directions will change. The phase velocities in the composite material are directly related to the elastic constants through the Christopher equa-
Figure 1 shows an example of ultrasonic wave propagation in a laminate immersed in water. The example shows pure modes and not pure modes due to the anisotropic nature of the laminate. It is only in the principal directions pure modes can propagate. In other directions one quasi longitudinal (qL), a fast (qT₁) and a slow (qT₂) quasi transverse waves are excited [4-5].

Ultrasonic simulations may also be helpful to determine the ultrasonic properties in anisotropic laminates and larger subcomponents [6-8]. As an example, ultrasonic beam deviation with respect to direction of propagation is illustrated in Figure 2. The left image shows the energy of the beam from a 45° transverse wave produced by a contact transducer in an orthotropic laminate, while the right image shows the beam produced by the same transducer in an isotropic laminate. The beam energy is steered towards the stiffest orientation in the orthotropic laminate. The beam is modelled in CIVA using the synthesis of impulse response achieved via a “pencil method” and applied to elastodynamics [9]. The two examples in Figures 1-2 demonstrate the need for calibration standards to assure reliable ultrasonic inspection of composite parts.
2.1 Need for ultrasonic standards

Very few ultrasonic standards exist for testing of composite parts. Most of them are developed for aerospace applications [10] and some are not public available, but developed internally by wind rotor blade manufacturers. To ensure accurate and reliable inspection ultrasonic testing equipment must be calibrated so that scans taken by different operators are comparable and can be compared with NDT norms. For steel components this is accomplished through calibration standards and well defined test blocks. The choice of calibration standard is depending on the NDT testing technique, the type of flaw and the material. For composite parts it is required to prepare a test block from the same material composition, manufacturing, geometry and surface condition as that to be tested. Test blocks with flat bottom holes, side drilled holes or Teflon foils are often applied. Figure 3 shows an example of a test block with flat bottom holes to be used for blade inspection. The advantage is that the test block and the test object will have the same properties as that to be tested. The disadvantage is that the number of test blocks will be high to cover a complex composition like a wind rotor blade. The lack of standards and the requirements to test blocks are some of the main barriers for small- and medium-sized enterprises (SMEs) to enter the wind blade market.

Figure 3. Test block with flat bottom holes

2.2 The Industry’s Composite Laboratory

The Industry’s Composite Laboratory is a new partnership between FORCE Technology, The Technical University of Denmark and Aalborg University that will assist companies in developing the knowledge and competences needed to take steps into the wind blade business. In this partnership SMEs are introduced to composite oriented production processes, which aim to provide all the development and production steps i.e. design and concept development, material selection, calculations, manufacturing and quality control. The aim of more quantitative ultrasonic material characterization is to create a better correlation between observations and ultrasonic imaging. Figure 4 (left) shows an automated ultrasonic scanner for detailed inspection of pre-production or subcomponent blades. Prototypes can be fully submersed in water or scanned in contact mode. Figure 4 (right) shows a cross sectional image of a component with porosity. The image is generated with an environmental scanning electron microscope (
ESEM) with high resolution. In terms of reliability it is important that the AUT-method is
calibrated properly to obtain a quantitative evaluation of defects in the composite part.

![Automated ultrasonic scanner for prototype scanning](image)

**Figure 4.** Automated ultrasonic scanner for prototype scanning (left). ESEM-image of composite part with porosity (right)

### 2.3 What can be found?

Detection of defect types mentioned in Table 1 is the aim for nearly all AUT-systems. A par-
ticular concern in very thick GRP laminates is dry areas and wrinkle detection. Both defect
types lower the mechanical strengths of the structure and may lead to failure in the particular
locations they appear. Consequently, to repair the structure in the proper way, localization and
extend of these defects have to be measured as precise as possible.

| Table 1. Defect types found in the design, the production and in installed blades |
|----------------------------------|-----------------|-----------------|
| Design                          | Production      | Installed       |
| Dry areas                       | Dry areas       | Impact          |
| Porosity (voids) / foreign bodies| Waviness        | Waviness        |
| Delaminations                   | Delaminations   | Delaminations   |
| Bonded joints of spar cap and shear web | Repair areas | Ingress of moisture |

#### 2.3.1 Dry areas

Dry areas, porosity (voids) and delaminations are often caused by lack of resin infusion of the
fibres. The main course for lack of resin may be failure in the mixing process or insufficient
vacuum. Figure 5 illustrates the ability to penetrate, locate and size flaws in thick 100 mm
GRP laminate, built of 6 layers. Teflon foils are placed in different depths and clearly located
in the P-scan image, showing a top-view, a side-view and an end-view of the thick GRP. A
dynamic gate is set in 90 mm depth and the top-view sizes the Teflon foil to 25 mm in diam-
eter.

#### 2.3.2 Waviness

Waviness, wrinkles and undulations are misalignment of fibres due to thermal stresses in the
production process or non intended bending of plys in the layup. Wrinkles are often occurring
in load-bearing spar cap/girder structures, mainly containing unidirectional (UD) fibre layup.
The characteristic fibre deviation with UD fibre waviness is loading the UD fibres unintentionally in transversal direction. Polymer matrices will overload, degrade and loose the inherent ability to carry load. Without the intra-bonding from matrices, the fibres become decoupled and fragile. The effect with matrix degradation makes the blade snap in pieces due to fatigue overload. Due to the dynamic load on blades in operation, fatigue cracks in spar cap laminates occurs early and may lead to blade failures. Once the appropriate AUT-method has been developed and critical verified on test blocks with artificial wrinkles the location, depth, length and height of the wrinkle can be determined, as illustrated in the P-scan image figure 6 (left). Figure 6 (right) shows a corresponding line scan for sizing and reporting the wrinkle.

![Figure 5. P-scan image showing top-view, side-view and end-view of GRP laminate with Teflon foils](image1)

![Figure 6. P-scan image showing top-view, side-view and end-view of GRP with artificial wrinkles (left) and line scan showing selected position (right)](image2)

A provisional specification for judgment of out-of-plane (ie. through thickness) wrinkles is illustrated in Figure 7, where $H$ is the peak height and $L$ the half wavelength of the wrinkle. A reporting level for a wrinkle would be [11]:

$$H$$
\[ H \geq 3 \text{mm} \quad \text{and} \quad L_{1,2} \leq 50 \text{mm} \quad \text{.................................. (1)} \]

and the wrinkle aspect ratio or average angle:

\[ \frac{H}{L} \cdot 100 \geq 6 \quad \text{or} \quad \alpha_{av} = \tan^{-1}\left(\frac{H}{L} \cdot L^{-1}\right) \geq 3^\circ \quad \text{.................. (2)} \]

Figure 7. Definition of peak height (H) and half wavelengths (L)

3. Reliable AUT in the blade production phase

The P-scan System 4 and the P-scan Stack System is developed for on-site automated ultrasonic inspection and supports battery operation, scanner controller and water supply. The P-scan Stack System offers in addition phased array (PA) imaging with a high dynamic range and amplitude resolution. A range of intelligent PA-probes are also supported [12].

3.1 Inspection time is a critical factor

The majority of blade manufacturing plants are specialized in producing a specific type of wind rotor blade, often in one or several parallel production lines. Space between the different lines is limited and specific solutions for horizontal and vertical position blades are requested. A critical factor is the time for inspection the load bearing parts of the blade after it leaves the mould. In order to optimize the production capacity the time for scanning a single blade is a limiting factor which should be minimized. While calibrating the equipment and reporting of findings can be done before and after scanning, the total inspection time is mainly composed of two components. The time it takes for scanning each part of the blade - the downwind and upwind side - and the time consumption for repositioning the scanner after scanning the first side. The time for automated scanning depends on the pulse repetition frequency of the ultrasonic system. In practice also its ability to support different probes with sufficient water coupling. Compared with traditional meander scanning, the scanning time can be minimized by different strategies which can be separated into: screening, full coverage and critic part methods. Table 2 gives an overview of the different scanning strategies.

3.1.1 Screening method with single element probes

Screening methods apply ultrasonic single element probes that are moved in a zigzag pattern and the resulting data are merged to present a P-scan image. To speed up the scanning, probes follow a scan path which typically is wider in the root area and narrower in the tip region of spar caps. For horizontally oriented blades a go-cart type scanner was developed, called AMS-46, which is a self-propelled crawling scanner, remotely controlled by the inspector. For vertically oriented blades a scanner (AMS-69) was developed for scanning in sections and in each section a screening of the local section is performed.
3.1.2 Full coverage method with multi channel probes or phased array
For vertically oriented blades full coverage scanning is also available with a multi channel probe array moved by a mobile, self-propelled truck (AMS-71). The multichannel array consists of a high number of single element probes organized according to the critical defect size and covers the width of the load bearing parts. Phased array probes may also be applied. The AMS-71 gives the fastest scanning time, reaching less than 8 m/min. The time for inspection of long rotor blades over 60 meter is less than 60 minutes, with both blade sides covered [13].

3.1.3 Critical part method
A new scanning method offers scanning by a statistical approach. In this method only the critical part of the blade is scanned by a newly patented crawler robot [14]. The critical part of the blade may be identified by a priori knowledge of the component obtained in the blade design phase. Visual indications may be identified with an unmanned aerial vehicle (UAV) drone with an optical camera [15].

<table>
<thead>
<tr>
<th>Screening method</th>
<th>Scanner: AMS-46 or AMS-69</th>
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<tbody>
<tr>
<td>Full coverage method</td>
<td>Scanner: AMS-71</td>
</tr>
<tr>
<td>Critical part method</td>
<td>Scanner: Crawler</td>
</tr>
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</table>

Table 2. Automated ultrasonic P-scan strategies

4. Reliable AUT for installed blades
During blade operation, the actual structural condition has to be checked periodically, avoiding valuable downtime. With hub heights of more than 100 meters and blades of 60-80 meter
length access to the blade is a challenge. Moreover strong winds and limited available working hours also limits the inspection window. Tough weather conditions like gusts, rain, snow, hail and thunderstorms also complicates reliable automated inspection of wind rotor blades. Table 3 lists the most common methods to access an installed wind rotor blade. Rope access with professional rope access technicians (SPRAT) is performed with a manually operated scanner (MWS-6) mainly used for semi automated inspection of composite parts. It is developed to be portable for random spot check of installed blades. Crane access equipped with working baskets and suspended platforms can also be applied with particular on-site inspection in mind.

For this purpose the AMS-64 scanner is designed for automated inspection of wind rotor blades and scanner mechanics is equipped with two individual controlled Y-modules, each carrying two transducers. The whole system is contained in two boxes. For attachment to the blade, suction cups controls are applied [16]. Various smart platforms and blade-guided robot systems is also developed, but have been applied with limited success. Moreover, UAV drones and unique blade crawling robots are currently developed for remotely controlled NDT inspection on vertical blade surfaces - on-shore as well as off-shore [17-19].

Table 3. P-scan access technology for scanning installed blades

<table>
<thead>
<tr>
<th>Access method</th>
<th>P-scan</th>
</tr>
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<tbody>
<tr>
<td>Rope access with SPRAT-certified technicians</td>
<td>MWS-6</td>
</tr>
<tr>
<td>Crane access equipped with working baskets or suspended platforms</td>
<td>AMS-64</td>
</tr>
<tr>
<td>Bladed-guided working Platforms</td>
<td>AMS-47 on FF360</td>
</tr>
<tr>
<td>Crawling scanner robots clinging to the blade surface</td>
<td>Crawler</td>
</tr>
<tr>
<td>UAV mini-helicopter for visual inspection</td>
<td>UAV visual inspection</td>
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5. Conclusions

The paper discusses a range of automated ultrasonic non-destructive inspection solutions for reliable inspection of the wind rotor blade throughout its lifetime. Different aspects of automated inspection are discussed addressing problems related to the design, the manufacturing and the operation of wind rotor blades. In the design phase of blade manufacturing a detailed automated inspection of pre-production blades gives reliable information of the complicated blade layup. The information is based on ultrasonic measurement in calibration blocks, classical material test and manufacturing knowledge. In the blade production phase, inspection time is a critical factor and different scanning strategies can be applied. For installed blades, on-shore as well as off-shore, access to the blade is a major concern. An overview of different access systems and the corresponding automated scanner is discussed. For reliable inspection of the wind rotor blade throughout its lifetime it is important to apply the same automated ultrasonic method in the design phase, the production phase and for installed blades.
Acknowledgements

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References


12. P-scan Stack System and scanners (www.P-scan.com)


