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ReNEWiT

Development of New and Novel Automated Inspection Technology for GRP Wind Turbine Blades

Horizontal Research Activities Involving SMEs

Co-operative Research

Publishable Final Activity Report

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TABLE OF CONTENTS

1. Project Execution

1.1. Project Objectives

The monitored and predicted growth of wind turbines in Europe indicates that the output from these sources has been increasing at approximately 30% per annum between years 1993-1999 and that the trend is set to continue between 2002-2010. This expansion could be supported by accessing the offshore market that is capable of generating large energy volumes at a reduced degree of societal impact or through the use of larger turbines elsewhere. Blades of over 61m are in current production and even larger blades are being considered to service the required outputs. Blades this size must be manufactured in a cost effective manner using cheap, strong and lightweight materials. Glass reinforced plastics (GRP) are used extensively, because they are lightweight and corrosion resistant. One major issue that has arisen through the desirable expansion in the use of this material is the lack of testing techniques suitable for the rapid and accurate inspection of large areas. The development of suitable Non-Destructive Testing (NDT) techniques is essential to allow European wind turbine blade (WTB) manufacturers to successfully employ the most desirable materials to achieve lightweight designs that can maximise the efficiency of the components and provide a competitive advantage over non-European manufacturers.

Although the rotational speed of large turbines is relatively low (12 to 17 RPM), the tip speeds can reach in excess of 190km/h. The consequences of critical damage due to impacts or lightning strike can be the shedding of large pieces of blade which, given the windy conditions required for operation, can sail for distances of up to 400m. Regular, cost effective, inspections can reduce the risk of such catastrophes and the ReNEWiT project seeks to develop automated NDT techniques that will provide an integrated solution to this requirement.

The scientific and technical objectives are:

(1) To significantly develop and improve NDT techniques, in a step change to their current capability, in order that WTB defects such as Zero Volume Unbonds are detected early in the manufacturing process.
(2) To deliver NDT techniques, optimised for use on the prototype equipment developed.
(3) To conduct inspections faster and hence reduce installation downtime by automating NDT techniques.
(4) To increase accuracy, by eliminating operator subjectivity and increase safety and reduce instances of failure.

1.2. Approach

The project was divided into a number of stages:

- The types and sizes of defects and the structure they were likely to occur in were identified.
- Samples of such structure containing realistic artificial defects were designed and manufactured.
- Radiographic, shearographic, ultrasonic and thermographic inspection techniques were devised to detect the defects sought.
- Hardware was developed to enable the application of these techniques on the samples previously manufactured.
- A robotic scanning system was designed and built capable of carrying the NDT systems developed.
- The NDT systems were integrated with the robotic scanner.
- A programme of trials on large blade samples was carried out to test functioning of the hardware and software.

1.3. Project Achievements

The ReNEWiT project has resulted in the following major achievements:

- A set of samples has been designed and produced covering all the main types of structure of interest. Artificial defects have been produced in the samples to mimic the types and sizes of defects sought.
- A Compton Backscatter digital radiography system has been designed and built.
- A dual laser shearography system capable of separately resolving in-plane strain has been developed and produced
- A pulsed thermography system has been built using an advanced flash excitation system. In addition a lighter version was developed capable of using hot air excitation.
- An ultrasonic technique known as Continuous Wavelet Transform was developed. This allows relatively low frequency probes to be used whilst preserving near surface resolution.
- A phased array ultrasonic system capable of rapid, large area coverage using very little water was developed.
- A robotic scanner capable of carrying and controlling the above systems in order to inspect all areas of a wind turbine blade surface was designed and built.
- The above systems were integrated with the scanner to produce the ReNEWiT wind turbine blade inspection system.

1.3.1. Samples

A set of samples has been designed and produced covering all the main types of structure of interest. These include representative, full width sections of blades containing real and artificial flaws, sections of the leading and trailing edges of the blades, and GRP coupons containing controlled levels of impact damage. The flaws represented include lack of adhesive in glue lines, barely visible impact damage (BVID), and "kissing" bonds. In addition a full width sample of blade weighing over 300kg was shipped to the robotic scanner developer, Zenon, where it was vertically mounted in a custom designed stillage. Figures 1 and 2 show examples of the samples produced.

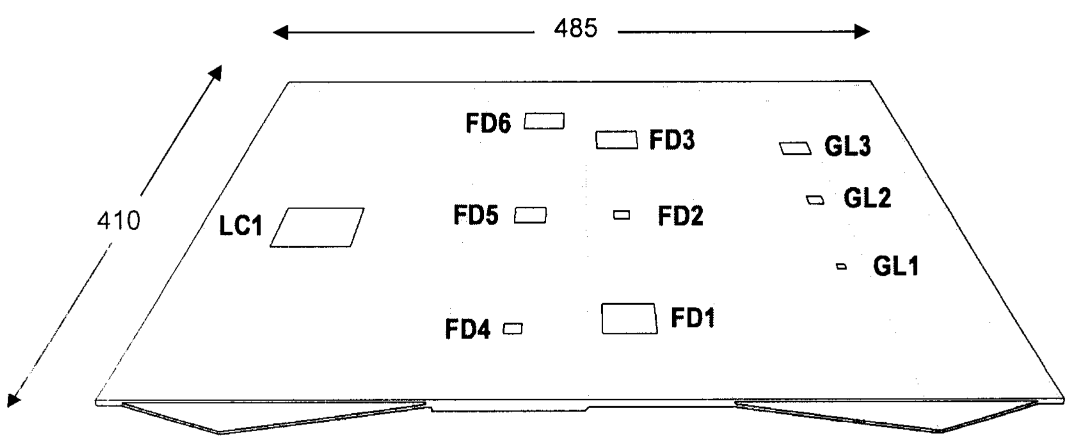


Figure 1: Flat leading edge sample. FD are flange defects, GL are defects between the gel coat and laminate and LC is a defect between the laminate and core (dimensions in mm).

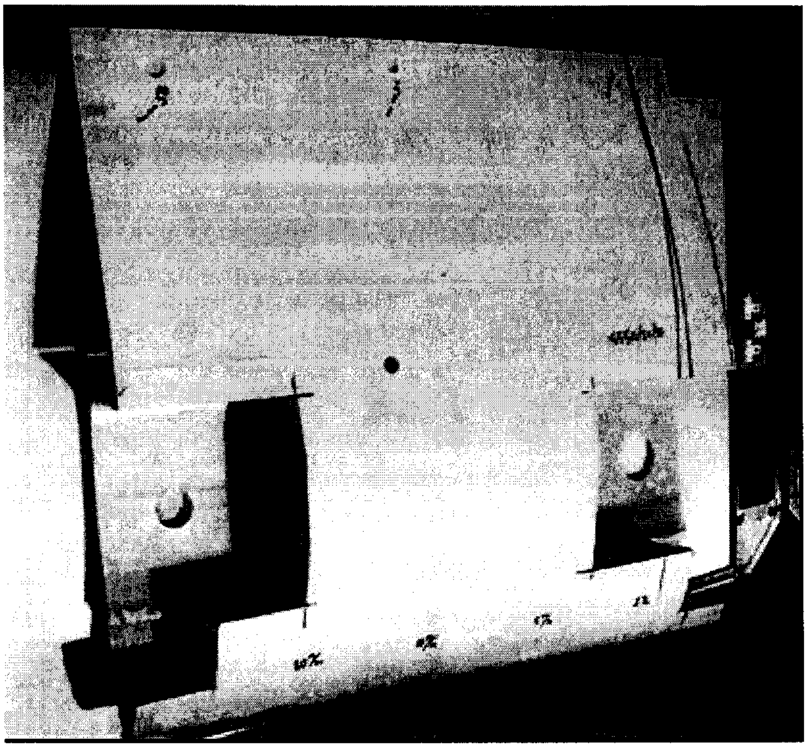


Figure 2: WTB sample containing various artificial defects

1.3.2. Compton Backscatter System

X-ray Compton back scattering is a relatively new NDT technique, and is carried out by measuring the amount of scattered soft X-rays from a test object. As Compton scattering occurs in all directions, this technique has the advantage of placing the X-ray source and detector on the same side of the test object, as opposed to traditional radiography where access to both sides is required. Figures 3(a) and 3(b) refer.

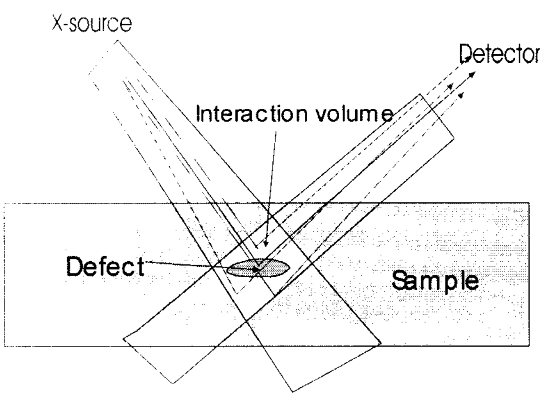


Figure 3: Compton Backscatter technique

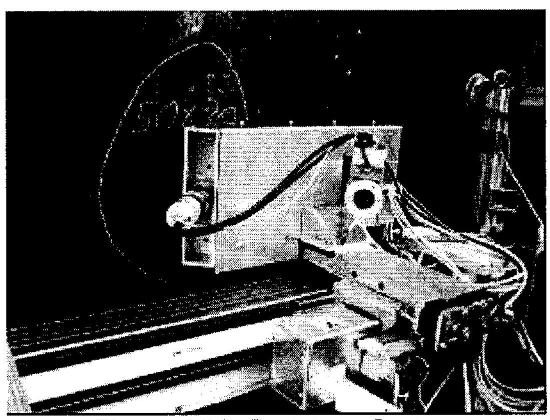


Figure 3(b): Prototype System

The prototype is designed to record scattered X-ray counts as a function of position of the detection volume related to the sample, f(X,Z). An X-scan represents a density profile along the sample, and flaws where the density and / or structure differ from the unflawed region can hence be identified. The Z value of the X-scan defines the depth in the sample from where the density profile is obtained. A Z-scan represents a density profile through the sample at the X value. Figures 4(a) and 4(b) show the sample and scan line and the results respectively. The drop in scattered radiation caused by the artificial defects is clearly visible as the two troughs labelled 5 and 6.

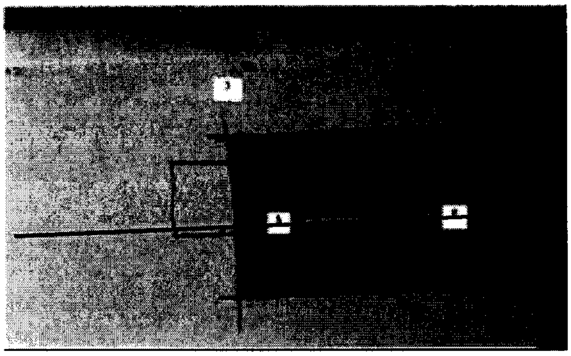


Figure 4(a): Sample and direction of scan

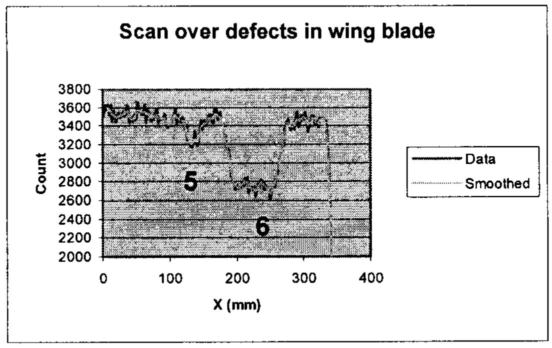


Figure 4(b): Defects 5 and 6

1.3.3. Dual Laser Shearography System

Conventional shearography, using a single laser, is sensitive to out of plane strains in a component. It is thus good at detecting disbonds in a composite component (i.e. separation between different parts bonded together). To identify delaminations, i.e. separation or weak bonds within laminations of a composite material or cracks, it is necessary to also be sensitive to in-plane strains. For this, a novel, prototype twin laser system has been developed by Laser Optical Engineering. This system is currently capable of isolating in-plane and out-of-plane components of strain and thus being able to detect delaminations, cracks and disbonds independently, thus discriminating between them. The Worshipful Company of Scientific Instrument Makers recently presented LOE with their Annual Achievement Award for the development of this system. The system is shown deployed on the scanner in Figure 5. The screen shows impact damage in a large turbine blade sample. Figure 6 shows a wrapped and an unwrapped colour image of a 25mm spar to skin bondline defect.

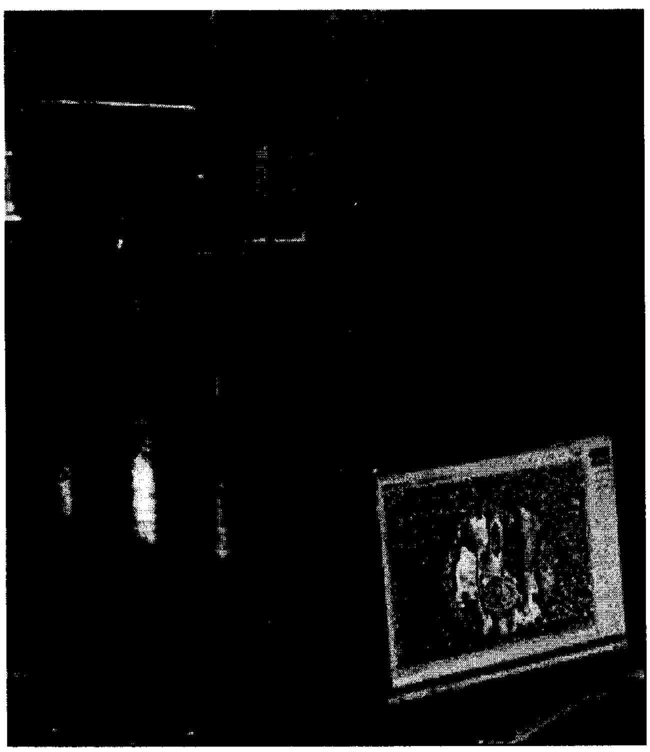


Figure 5: Dual laser system deployed on scanner

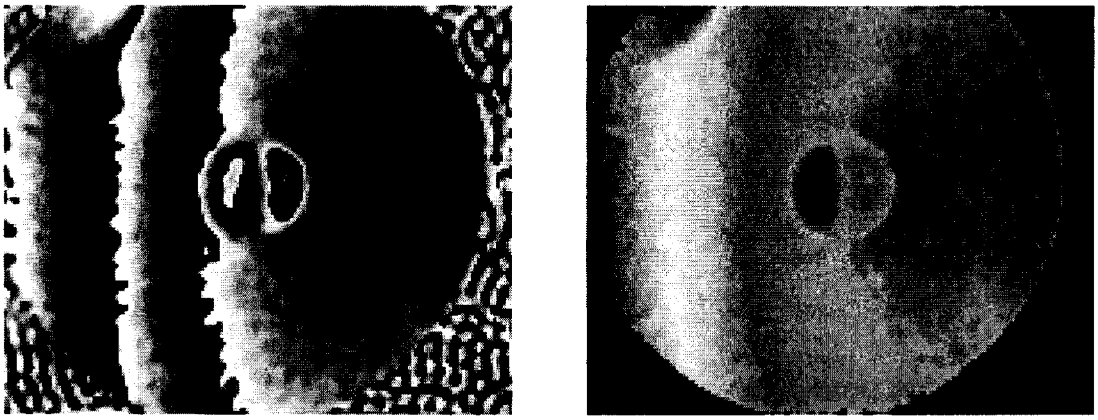


Figure 6: Wrapped and unwrapped colour image of a 25mm spar to skin bondline defect.

1.3.4. Pulsed Thermography System

A pulsed thermography system had been developed and supplied by LOT. The system can be used with powerful flash lamps to heat the surface over a very short space of time for rapid inspection in stand alone mode, or as in this case using active heating from a heat gun and a highly sensitive thermal camera. This resulted in a much lighter system able to be integrated with the robotic scanner and used simultaneously with the other NDT systems developed. The pulsed thermography system has proved very successful at detecting a range of defects in all areas of the turbine blade. It is particularly useful for detecting skin to spar unbonds and disbonds and voids in the adhesive. Figure 7 shows the thermography system deployed on the scanner. Figures 8(a) to (c) show raw, colour, and 3D images of the defect in Figure 6 above.

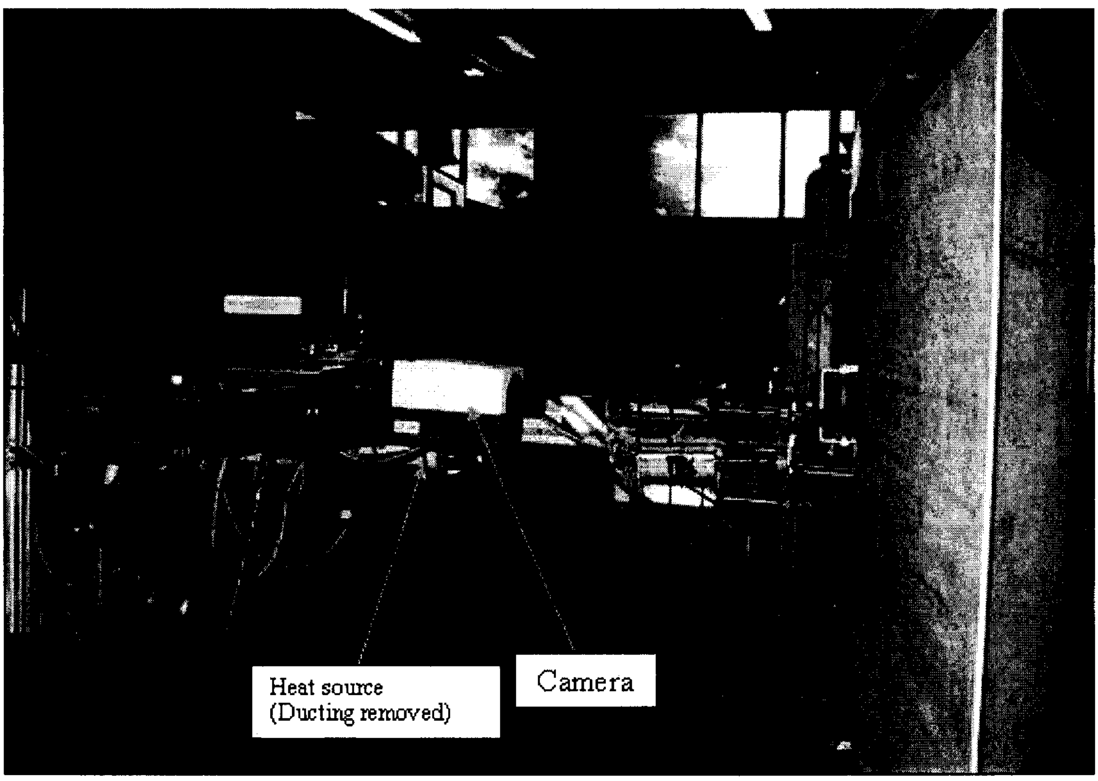
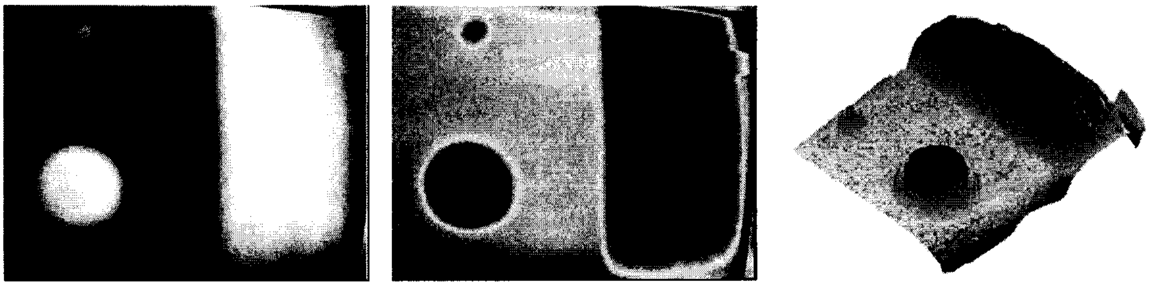


Figure 7: Thermography system deployed on the scanner.



Figures 8(a) to (c): raw, colour, and 3D images of the defect in Figure 6 above

1.3.5. Continuous Wavelet Transform

An ultrasonic technique known as Continuous Wavelet Transform was developed. This allows relatively low frequency probes to be used, as required by highly attenuative materials such as those found in wind turbine blades, whilst preserving near surface resolution. The Continuous Wavelet Transform (CWT) decomposes a signal into wavelets, small oscillations that are highly localized in time. Whereas the Fourier transform decomposes a signal into infinite length sines and cosines, effectively losing all time-localization information, the CWT's basic functions are scaled and shifted versions of the time-localized mother wavelet. CWT is a powerful tool for mapping the changing properties of non-stationary signals. It is used to construct a time-frequency representation of a signal that offers very good time and frequency localization. It is especially useful in identifying signals from defects close to the surface that would normally be lost in the ring down from the surface interface echo. Figure 9 shows the power curves from a defect free zone (red) and a near surface defect (blue).

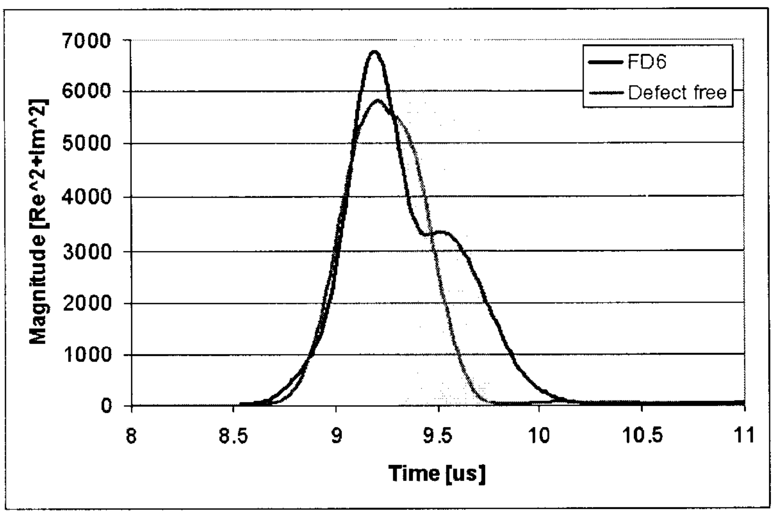


Figure 9: Power curve of wavelet transform

1.3.6. Phased Array Ultrasonic System

A phased array ultrasonic system capable of rapid, large area coverage using very little water was developed. It has a scanning phased array system utilising a 128-channel pulser receiver system that is capable of generating beams from up to 32 active channels. The system has a custom, high-speed data capture card which controls the beam-forming electronics and processes the raw ultrasound data to deliver high frame rate B-scans and rapid processing for C-scan data. Depending on the number of beams generated and the data density, B-scan frame rates between 100 to 300 times per second can be achieved permitting fast, high resolution scanning of large areas.

The array is deployed in a water-filled tyre, which when used with a light mist of water, produces consistent coupling and permits high scanning speeds. Alignment of the probe with respect to the surface is critical, so a custom, self centring probe holder was designed to cope with the highly curved surfaces of typical wind turbine blades. The system can be deployed manually or can be controlled automatically by the robotic scanning system. Figure10 shows the system attached to the robotic scanner.

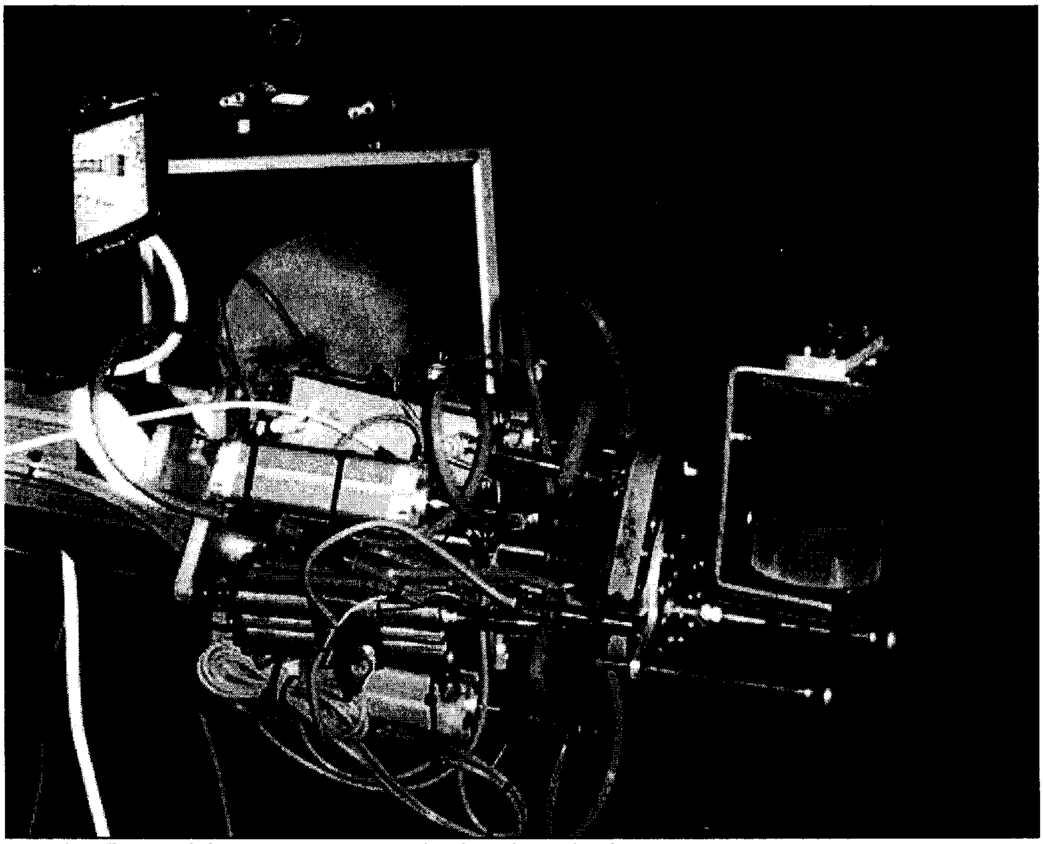


Figure 10: Phased Array system attached to the robotic scanner.

The software can display data in several ways. Figure 11 shows the A, B and C-scan presentations resulting from scans of defects GL2 and GL3 of the sample in Figure 1 above.

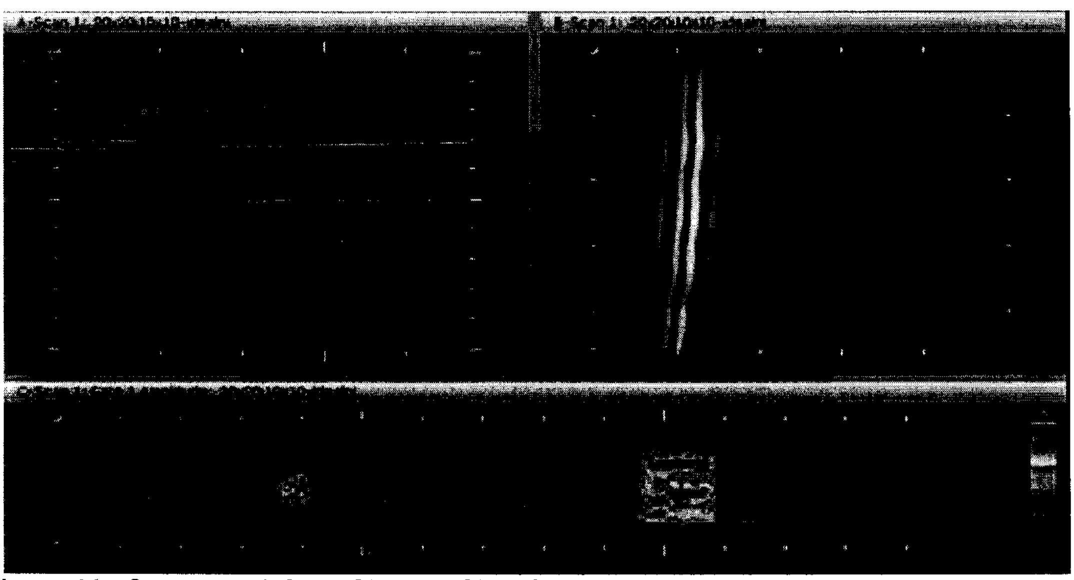


Figure 11: Scan over defects GL2 and GL3 of the sample in Figure 1 above

1.3.7. Robotic Scanner

Partners Zenon and Miltech have developed a light weight, robust scanning gantry mechanism. The system is intended to deploy the developed NDT methods on a stationary wind turbine blade when positioned on the vertically moving external maintenance elevator.

As well as being a light and extremely stiff structure, the scanner has three key elements:

The Z axis arm uses pneumatic actuators to ensure a constant contact pressure with the turbine blade surface. This is important as the blade varies in thickness by as much as 2m from hub to tip and some NDT systems require a constant distance between instrument and blade surface to be maintained. In an emergency the Z arm is able to retract rapidly to a safe distance from the blade. Proximity sensors are able to detect when the blade edge is reached and stop or start scanning as required.

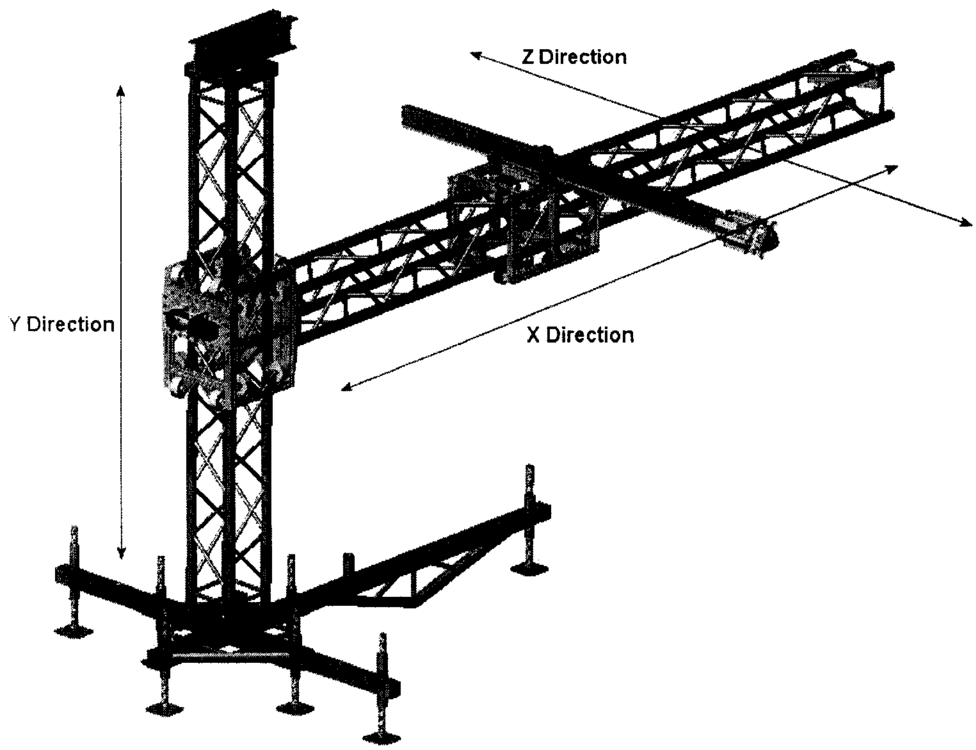


Figure12: Main scanner and Z axis arm.

The end effector is vital to the operation of the system. It maintains the correct orientation of the ultrasonic probe with respect to the surface of the blade and delivers coupling water to the correct side of the probe depending on the direction of scanning. The half Stewart platform design allows up to 40 degrees of movement in all directions to ensure the surface contours are accurately followed. See Figure 13. Information about the surface geometry is then passed to the planet gearbox. For inspection systems that need to be still while capturing data, three suction cups can be deployed to hold the end effector firmly to the surface.

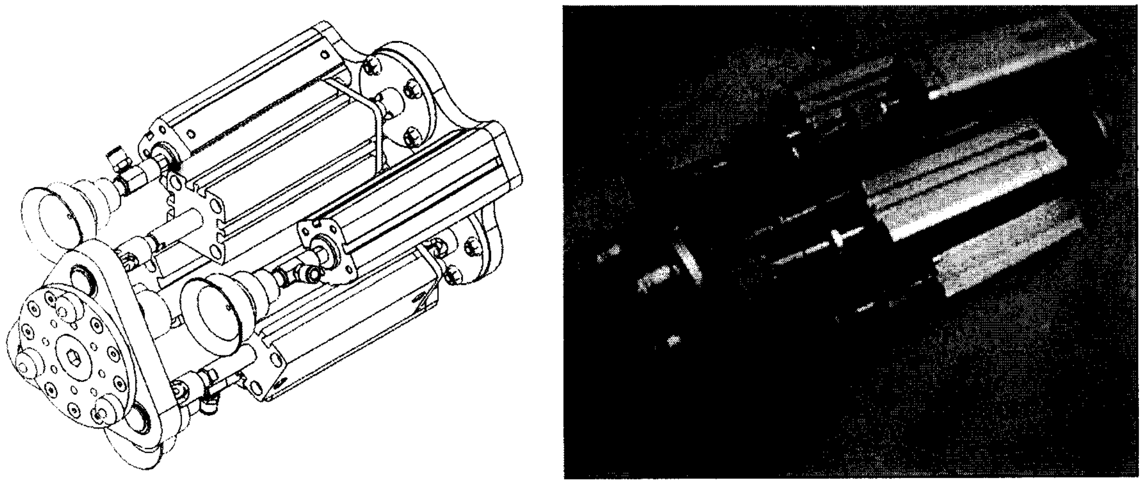


Figure 13: Prototype end-effector.

The planet gearbox was designed in order to enable the use of inspection tools that need to be deployed at an angle normal to the surface but are non-contacting or must maintain a significant separation. The length of each of the three end-effector pneumatic actuators is measured. With simple triangulation the angle of the end-effector top flange is calculated and is passed to the planetary-mechanism. This actuator moves the instrument along a linear slider while simultaneously the planetary mechanism rotates it to the correct angle. See Figure 14.

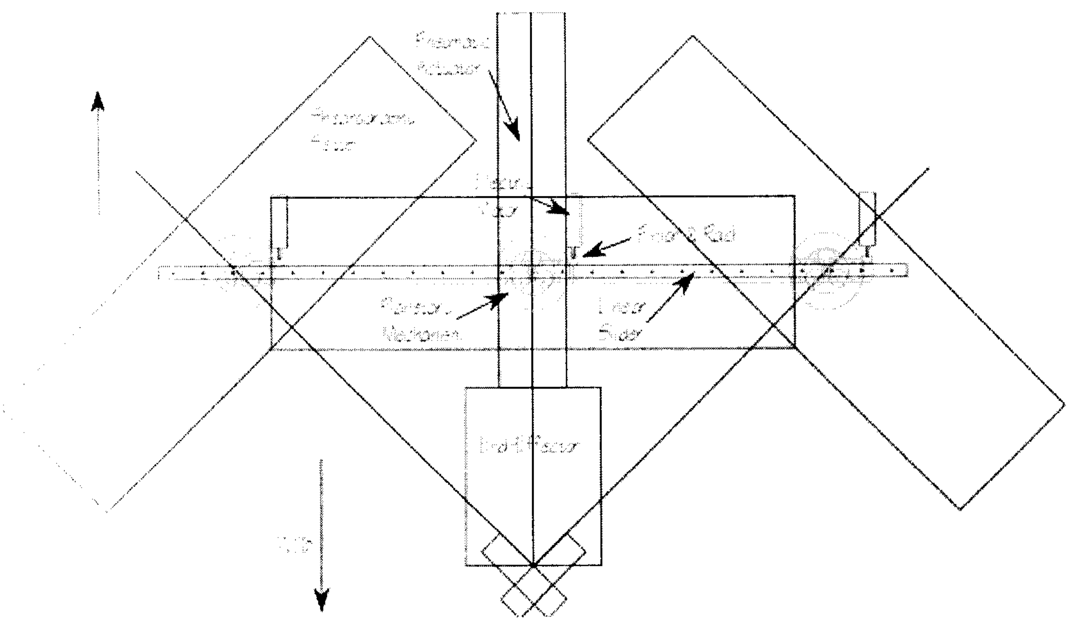


Figure 14: Schematic of planetary gearbox.

The versatile robotic scanner is controlled by a custom designed man-machine interface. The software is intuitive to use and enables control of the scanner and attached NDT systems through a familiar windows based application. Motion control can be via mouse, keyboard or joystick. Figure 15 shows a typical screen display from the control software.

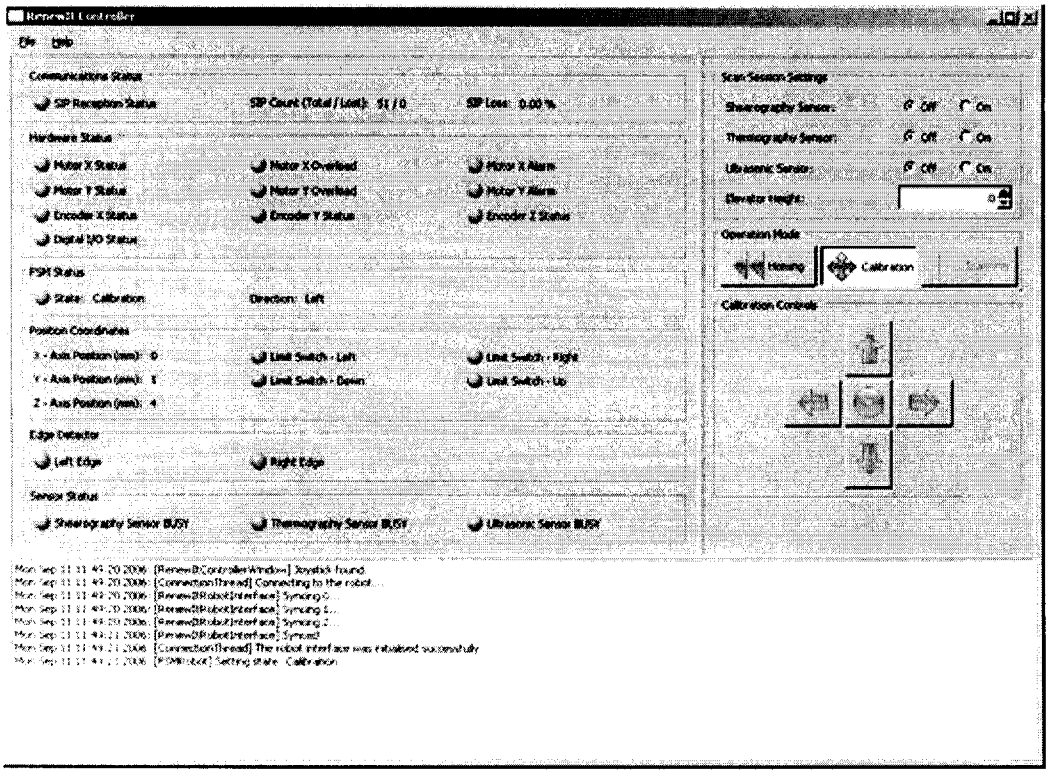


Figure 15: Screen grab from man-machine interface software

1.3.8. Integrated ReNEWiT scanning system

The ReNEWiT scanning system combines the advantages of the shearography, thermography, ultrasonic and robotic systems described above. It is able to scan the complete surface area of a 40m wind turbine blade when used in conjunction with a suitable maintenance elevator system and is operable by one man. The system requires a 220-240V 50Hz supply and a small quantity of water (approx 10 Litres/blade) when scanning using the ultrasonic module. Pre-programming of the NDT modules allows full control of the system from the man-machine interface. Figure 16 shows the system scanning a full size section of blade with the shearography module attached.

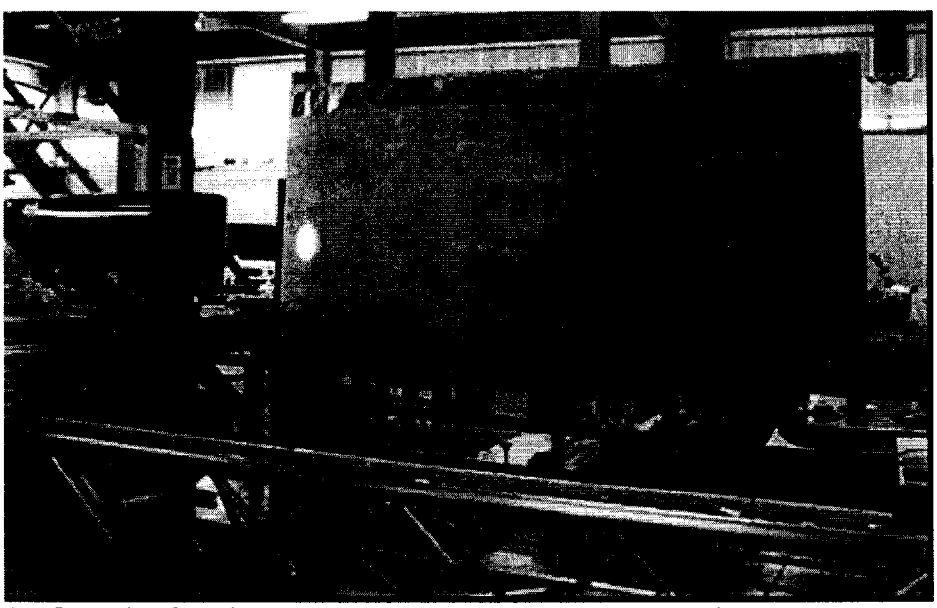


Figure 16: Scanning full width blade section using laser shearography

Figure 17 shows the ultrasonic scanning system passing over an area of impact damage in the large blade section. The system is able to scan the entire width of the blade in one pass.

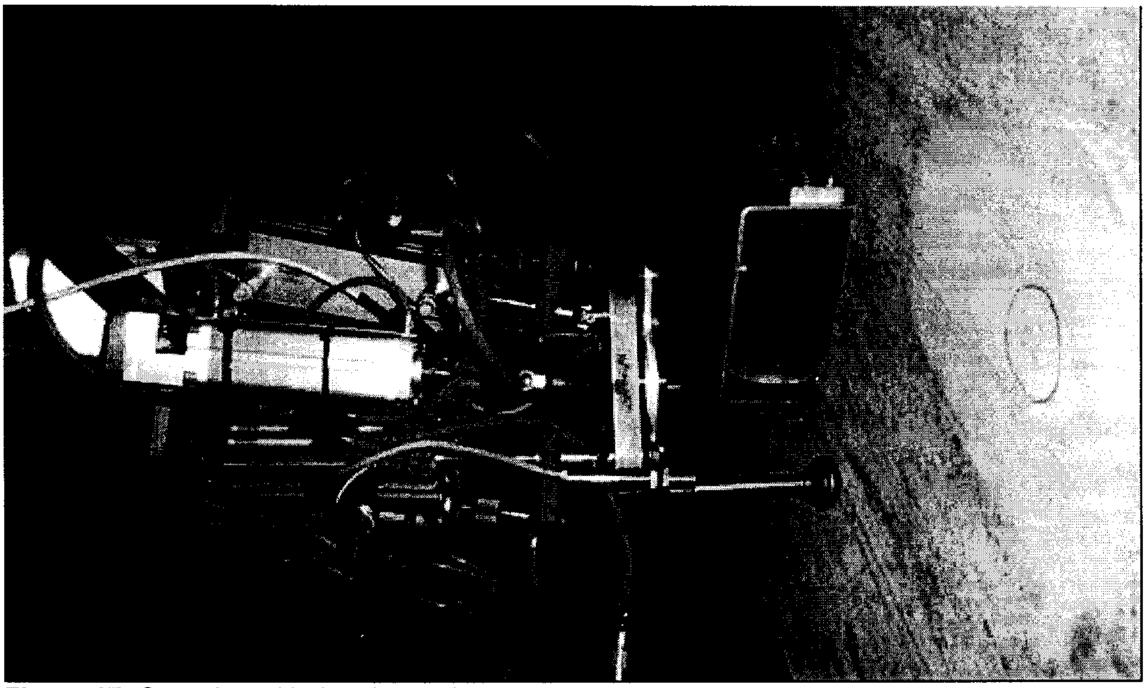


Figure 17: Scanning with the ultrasonic system

Figure 18 shows a typical full blade width scan with a defect present. Also clearly visible are the glue lines made by the applicator tool during manufacture.

Figure 18: Full width c-scan showing defect

Figure 19 is a close up of the impact damage area. The data is easily manipulated after acquisition is completed reducing turbine down time.

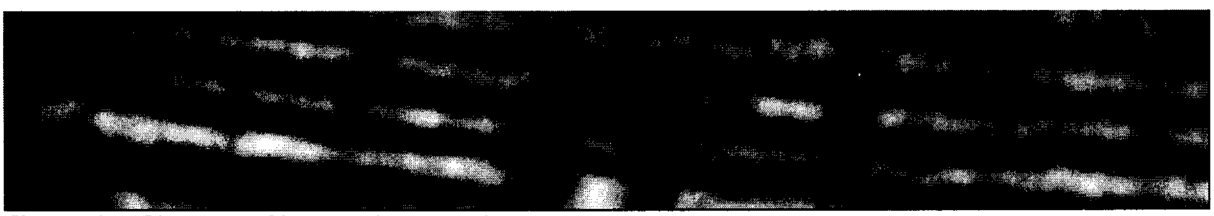


Figure 19: Close up of impact damage site

1.4. Project achievements against State-of-the-art

Most in-service inspection of wind turbine blades involves visual inspection from the ground using binoculars, and visual inspection from a gantry or lift system during blade cleaning or other routine maintenance. Obvious visual damage may be repaired on site with the blade installed. More serious damage requires replacement of the blade. Some semi automated UT systems do exist but are used infrequently due to the high cost of the laboratory intensive, time consuming scanning and data analysis and associated system down time.

The ReNEWiT project has developed a fully automated, multi method scanning system able to reach all areas of the blade and operable by a single operator. This automated system could drive down the cost of inspection by reducing scanning time, improving accuracy and repeatability, and minimising the risk of working at height to the operator.

Previous Laser Shearography systems have been sensitive to in-plane strain but have been unable to isolate the in-plane and out-of-plane strain fields. The novel dual laser system developed by LOE is able to optically isolate the in-plane and out of plane strain and display these separately. This greatly improves the ability to detect and characterise defects such as cracks and paves the way for further work to compare the in-plane strain field with FEA data to inform the design process. The loads required to produce strain data are very low and could result in smaller test rigs and shorter test times.

Although Ultrasonic area scanning systems have been available for some time, very few have been able to provide the rapid area coverage required for wind turbine blade inspection. Those that have are unable to cope with the difficulties of coupling to abrasive vertical services, which may be eroded and soiled with biological and chemical contaminants. When the requirement to use little or no water is also added into the equation, the wheel probe array system developed by NDTS provides a real step forward in meeting the need for an automated, ultrasonic area inspection system for the wind turbine industry.

The ReNEWiT wind turbine blade inspection system is the only prototype automated, multi-method, robotic inspection tool, that with further commercialisation, could provide a cost effective maintenance solution capable of being deployed on a variety of maintenance elevators.

2. Dissemination and Use

Full details of the ReNEWiT project and consortium may be found at
http://www.renewit.eu.com/
Figure 20 shows the home page of the ReNEWiT website.

Figure 20: ReNEWiT Website home page

For further information on specific areas of the project please contact the consortium partners. A brief description of each subsystem and the appropriate partner contact details may be found below.

2.1. The ReNEWiT Automated Scanning System

The ReNEWiT prototype system is intended to attach to a standard maintenance elevator. Although the system was designed to work with the Vestas Skylift elevator, the modular design allows customisation of the detachable base unit to suit any other suitable lift equipment. The scanner can cover all areas of the blade and is intended to be able to scan the full chord of a 40m blade. With the blade positioned vertically, a height in excess of 2m can be scanned before the supporting elevator needs to be moved. The developed system is able to carry and control pre-programmed ultrasonic, shearographic and thermographic inspection systems simultaneously. Some improvements to the speed and weight of the scanner are probably needed for full commercial implementation.

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2.2. Compton Backscatter System

The Compton Backscatter radiographic system showed a capability for detecting and sizing voluminous flaws in thicker sections of composite material. It is capable of detecting changes in density and providing depth and positional information.

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2.3. Pulsed Thermography System

The pulsed thermography system has proved very successful at detecting a range of defects in all areas of the turbine blade. It is particularly useful for detecting skin to spar unbonds and disbonds and voids in the adhesive. Some types of protective films applied to the leading edge may need to be removed.

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2.4. Dual Laser Shearography System

This novel instrument is capable of mapping surface strains and detects the presence of defects by showing the irregularities in the strain field that they cause when the structure is suitably stressed. Unlike conventional strain mapping systems, the ReNEWiT system can optically isolate the in-plane and out of plane components, which aids discrimination between defects such as cracks and disbonds.

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2.5. Dry Coupled Phased Array UT System

The ReNEWiT UT system had to cope with varying degrees of curvature, surface degradation due to erosion, impact damage and soiling. In addition it was required to provide consistent coupling using little or no water, while providing rapid coverage of large areas. All these things have been achieved whilst meeting the target requirement of being able to detect laminar flaws of 10mm diameter in the highly attenuative wind turbine blade structure. Although dry coupling is possible, a light misting provides optimum performance with very little water usage.

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2.6. Robotic Scanner

The ReNEWiT robotic scanner is able to accept and control a range of NDT and other systems simultaneously. The man-machine interface is intuitive to use and the machine may be controlled from wireless joystick or keyboard. The scanner is scaleable to meet almost any size of turbine blade or other large vertical structure and in addition to NDT, could be used for remote camera inspection, cleaning or other tasks requiring remote access.

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