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## DEVELOPMENT OF AN ULTRASONIC NDT SYSTEM FOR AUTOMATED IN-SITU INSPECTION OF WIND TURBINE BLADES

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### ABSTRACT

It is crucial to maintain wind turbine blades regularly, due to the high stress leading to defects or even damage. Conventional methods require shipping the blades to a workshop for inspection off-site, which is extremely time-consuming and very costly. This work investigates using pulse-echo ultrasound to detect internal damages in wind turbine blades without the necessity to ship the blades off-site. A prototype of 2D ultrasonic non-destructive testing (NDT) system has been developed and optimised for in-situ wind turbine blade inspection. The system is designed to be light weight so it can be easily carried by an inspector climbing onto the wind turbine blade for in-situ inspection. It can be operated in 1D A-Scan, 2D C-Scan or 3D Volume Scan. A software system has been developed to control the automated scanning and show the damage areas in a 2D/3D map with different colours so that the inspector can easily identify the damage areas. Experiments on Glass Fibre Reinforced Plastics (GFRP) and wind turbine blades (made of GFRP) samples showed that internal defects can be detected. The main advantages of this system are fully automated 2D spatial scanning and flaw displaying. It is potentially to be used for in-situ inspection to save maintenance time and hence considered to be economically beneficial for the wind energy industry.

**KEYWORDS :** *Ultrasound, Non-Destructive Testing, Wind Turbine Blade, Glass Fibre Reinforced Plastics, Defect Detection.*

### INTRODUCTION

Wind energy is one of the most important renewable energy resources. The EU has set a target to attain 20% of electricity from renewable sources by 2020, so the number of wind energy plants is increasing and the wind energy is expected to be the biggest contributor [1]. To avoid accidents and also minimise the down time of the wind energy plants, regular inspection, maintenance and repair of wind turbines are necessary. Due to the wind's irregular force causing heavy dynamic loads to the wind turbine, flaws and damages can exist in all components of a wind turbine, including turbine blades, tower, gears, generator bearings etc. [2]. However, due to high stress in the wind turbine blades, they are particularly susceptible to be damaged hence it is crucial to inspect and maintain them regularly [3-5].

Wind turbine blades maintenance plays an important role in the wind energy industry. The blades are about 15-20 % of the total price of a wind turbine and the market has been one of the fastest growing markets in the world [6]. It was also reported that the production of wind turbine blades grew by over 20% per annum in the last five years [7]. Wind turbine blades are mainly made from fibre reinforced composites i.e. glass fibre and carbon fibre. Due to the relatively low cost of glass fibre, it has been widely used for manufacturing wind turbine blades, although carbon fibre is becoming more and more popular [7]. In-service blades suffer from several degradation mechanisms, such as dis-bonding, delamination, fibre cracking, fatigue, UV degradation etc. Prior

to repairs, the blade has to be assessed using non-destructive techniques to identify any damage or flaw in the composite structure. This includes finding the damage location and assessing the extent of the damage. Thus non-destructive testing (NDT) is important in the wind energy industry. Conventional blade maintenance methods require shipping the blades to an off-site workshop for inspection, which is extremely time-consuming and costly.

This work investigates in developing a portable NDT system which would be suitable to be carried by an inspector climbing on the wind turbine blades for in-situ inspection. This paper reviews briefly a number of NDT methods and then concludes that ultrasound is suitable for building the inspection system. Section 2 presents a prototype of automated ultrasonic NDT system. Section 3 tests it on Glass Fibre Reinforced Plastics (GFRP) and wind turbine blade samples. This paper will finally conclude that the prototype is potentially to be used for in-situ wind turbine blade inspections.

## 1 REVIEW OF NDT METHODS

There are a number of non-destructive testing methods can be used to assess the quality of materials used in the manufacture process of turbine blades, such as X-Ray imaging, infrared thermography, tap testing and ultrasound [8-10]. However some of them may not be suitable for in-situ wind turbine blades inspection due to their dimensions, safety issues or accuracy [11].

X-Ray imaging is based on the different levels of absorption of X-Ray photons traveling through a material. It can be used to inspect a large number of materials including composites, with a sensitivity of detecting 1-2 % of change in material density [9, 12]. However X-Ray is usually operated in transmission mode and hence it cannot detect cracks parallel to the rays. In addition, the X-Ray emission may cause a health safety issue. Infrared thermography uses an infrared camera to capture the infrared radiation emitted by all objects above absolute zero according to the black body radiation law [12]. It can be operated as a passive approach which investigates the material's different temperature caused by degeneration of components. It can be also operated as an active approach which uses an external excitation to introduce additional thermal contrasts on the defective area which is expected to have higher temperature due to higher stress concentrated in the area [13]. Although the thermography method can produce a full-field image for a fast inspection, it is still not suggested in this work for in-situ wind turbine blade inspection since the passive thermography is only sensitive to the near-surface defects and the active thermography has a drawback of potentially damaging the composites by the external excitation. Tap testing is a technique that uses an impulse hammer to generate a reproducible sound on the testing material and then analyse the excited sound which relates to the frequency response of the vibration area [14]. Defective structures will produce the sound with different frequency spectrum. Although recent techniques use microphones to record the sound and apply digital signal processing methods for defect detection, the tap test is still hard to identify the defect types and sizes due to sufficient ambient noise and the difficulty of controlling the tapping force.

Ultrasonic testing is one of the most widely used NDT techniques in industry for inspecting composite materials e.g. CFRP (carbon fibre reinforced plastics) and GFRP which are the main materials for manufacturing wind turbine blades [15-23]. It uses an ultrasound transducer to generate ultrasonic waves which will propagate and interact with the medium. It may be reflected due to density changes in the medium caused by defects, delamination or interface dis-bonding. This work investigates into using ultrasound for NDT of GFRP and develops a fully automated 2D ultrasonic scanning system for the purpose of in-situ wind turbine blades inspection.

## 2 PROTOTYPE OF AN AUTOMATED ULTRASONIC NDT SYSTEM

Conventional ultrasonic NDT systems for inspecting composite materials are manually operated to collect and display one dimensional A-line ultrasound signal in a waveform. However this is time-consuming, inaccurate and it is hard to identify an area of defects. In this paper, a fully automated ultrasonic NDT system controlled by a computer has been developed for the purpose of in-situ

inspection of wind turbine blades. The system includes an ultrasound NDT system and an automated positioning system, which is portable and can be affixed to a wind turbine blade to detect internal defects. The A-line signal and the 2D C-Scan image can be displayed online during scanning, and the 3D volume data (A-line + 2D position) can be saved to the computer's hard disk for further investigation or signal/image processing after the scan.

## 2.1 Ultrasonic NDT system

Figure 1 shows that the ultrasonic NDT system consists of an ultrasound pulser-receiver (Opbox 2.0 from Optel Ltd, Poland) connected to a computer, and an ultrasound transducer (4 MHz, Model K4N-F from GE Ltd, USA). The pulser-receiver has a 3dB bandwidth from 500 KHz to 25 MHz, which can drive a wide range of ultrasound transducers. It connects to a computer via a USB cable. The computer uses the C/C++ DLL software interface provided by the manufacturer to communicate and control the pulser-receiver for sending and receiving ultrasound signals.

The transducer is a 4 MHz piston transducer with a diameter of 10 mm. The ultrasound frequency for NDT of composite materials is usually over 1 MHz, because of the higher frequency the smaller wavelength and hence the better spatial resolution. However in practice the higher frequency the higher attenuation in composites. It results in less energy going into the composites and hence a lower SNR (signal to noise ratio) signal. Preliminary experiments in this work have been carried out on comparing the performances of different frequencies (1 MHz, 4 MHz, 5 MHz and 10 MHz) on CFRP and GFRP. The 4 MHz K4N-F transducer has been found to be one of the suitable transducers for wind turbine blades inspection, in terms of the spatial resolution and the signal's SNR.

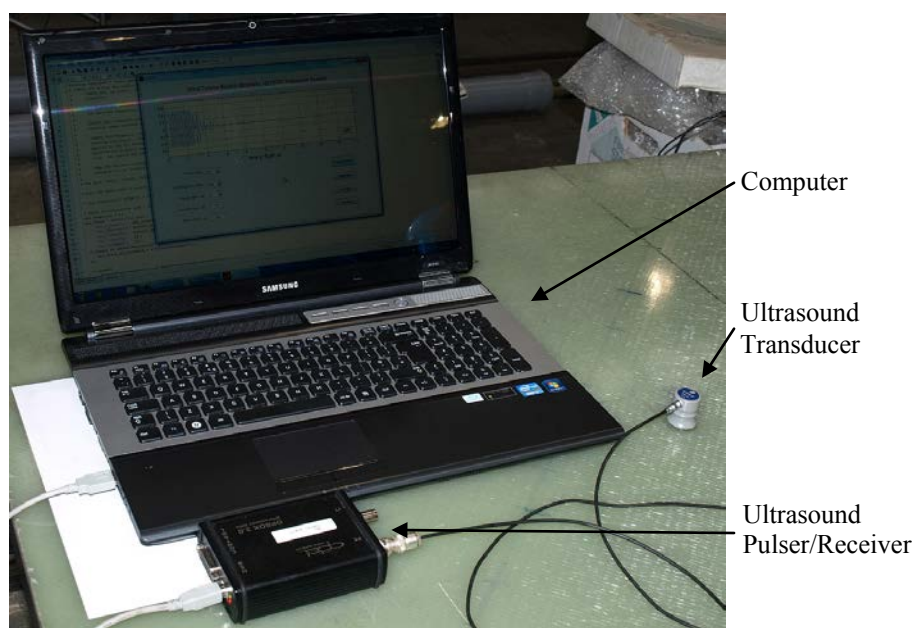


Figure 1: Ultrasonic NDT system.

## 2.2 Automated positioning system

The automated positioning system consists of a mechanised system to position the ultrasound transducer and an interface system to communicate with the computer. The mechanised system is about 500x500 mm width, including a 2-dimensional linear stage, an aluminium frame, 3 suction cups, 2 vacuum devices, and a pivot system (see Figure 2). The 2D linear stage consists of two

miniature linear positioners with stepper motors from Parker Hannifin Corporation, USA. The stage is supported by the aluminium frame (500x500 mm) and has a usable travel range of 483x483 mm, a maximum travel speed of 50 mm/s and an accuracy of 0.1 mm. The frame can be affixed to the surface of composite materials by the suction cups vacuumed by the vacuum devices showed in Figure 2. Each suction cup can provide a payload of 7 kg so the use of three suction cups in the system is more than enough to hold the whole mechanised system which is about 5 kg.

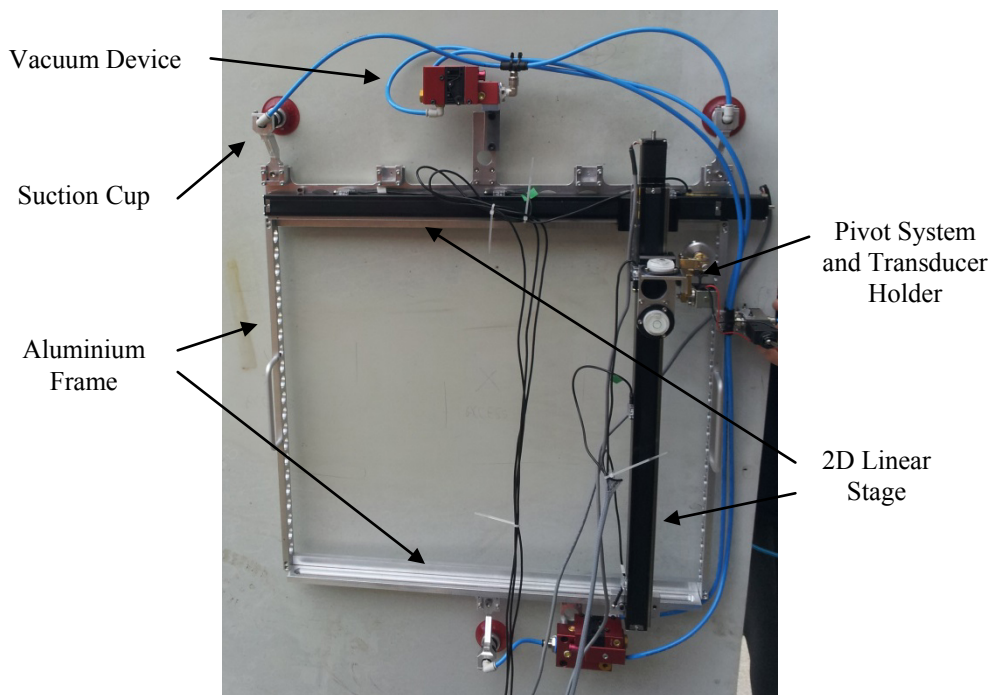


Figure 2: Automated positioning device vertically affixed to a wind turbine blade.

Since the system will move the ultrasound transducer point by point to inspect a certain area, the transducer has to be raised off the surface during traveling to avoid damaging it and be lowered down to contact with the surface during inspecting. The system uses a pivot system driven by a servomotor to raise and lower the transducer. In addition, there are 2 stepper motors used for the positioners. The servomotor and the stepper motors are driven by a motor controller with a Raspberry Pi (RS Components, UK) to provide a RS232 (serial port) interface with a computer.

### 2.3 System integration

The whole inspection system consists of the ultrasonic NDT subsystem showed in Section 2.1 and the automated positioning subsystem showed in Section 2.2. Both subsystems are connected to a computer via USB cables. A software system based on MATLAB (Mathworks, USA) has been developed to synchronously control the whole system including the pulser-receiver and the positioning device (see Figure 3a). The scanning procedure is illustrated in Figure 3b. The software system will send a command to the positioning system to raise the transducer and move to the next inspection point. Once the transducer arrives the inspection point, it will be lowered to contact the testing material and the system will collect A-line ultrasound signals. The above procedure will be repeated until an area has been scanned.

The software system has a Graphical User Interface (GUI) for setting parameters (e.g. ultrasound power, amplifier, data sampling frequency, scanning range etc.) to control the hardware. It can also display a C-Scan image at a specific depth during scanning. The image is produced by using a gate to select data from a specific depth from an A-line signal. During the 2D scanning, the

automated positioning system moves the transducer to sample the entire fixed depth zone to generate a 2D image. The colours on the image relate to the echo strength from the fixed depth zone.

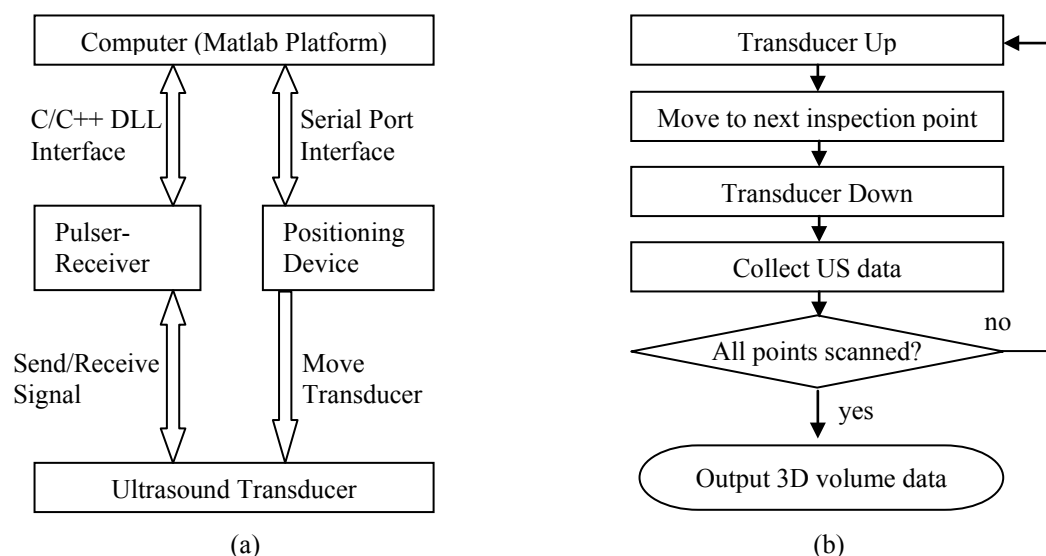


Figure 3: System integration of the automated ultrasonic NDT system. (a): System architecture. (b): Automated scanning procedure.

### 3 EXPERIMENTAL RESULTS

To test the automated ultrasonic NDT system, experiments have been carried out on GFRP and wind turbine blade samples. Ultrasonic gel was used on the surface of the transducer as an acoustic coupling medium. The scanning time of current system for one point is roughly 1 second (including raising, lowering and moving the transducer), so for a scanning area of 50x50 mm using a 5 mm step size, there are 100 points (10x10) to be scanned and hence the total scanning time is about 100 seconds. The scanning speed could be improved by optimising the software and hardware settings in the future.

#### 3.1 GFRP testing

Figure 4 shows a piece of 8 mm thick GFRP with three 30x30 mm defects which are measured 1, 2 and 3 mm deep respectively from the bottom. The GFRP was scanned using the automated ultrasonic NDT system on the top surface with a 5 mm step size. Figure 5 shows the C-Scan images at the depth of 8 mm with and without data average in the axial direction. In Figure 5a, the C-Scan image is showed at the depth of 8mm without any data average over the axial direction. The image is noisy and it is hard to identify the defect areas, since the sampling frequency of the ultrasound signal in the axial direction (A-line signal) is 100 MHz which is much higher than the ultrasound frequency of 4 MHz.

In Figure 5b, a 1 mm window was applied to average the C-Scan image in the axial direction. Three defects are showed in different colours, which can be easily identified. However, there are still some artefacts outside the defect areas due to the high level of noise in the ultrasound data. By applying bigger window sizes to the C-Scan image, Figure 5c and Figure 5d showed that the artefacts are reduced while the averaging window size increases. However, the defect areas may also be smoothed if increasing the window size.

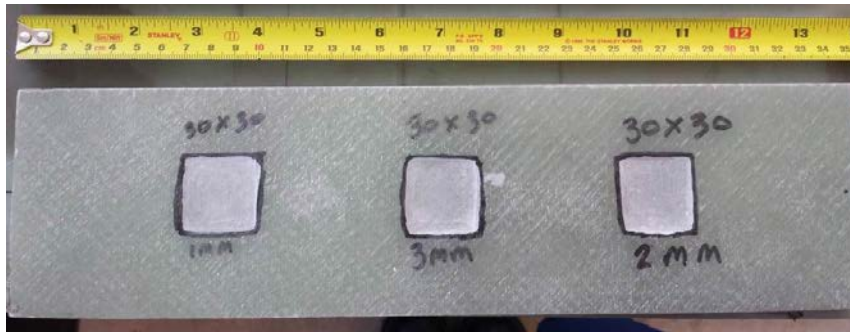


Figure 4: The bottom view of a piece of GFRP (8 mm thick) sample with three defects (30x30mm) measured 1 mm, 2 mm and 3 mm deep from the bottom.

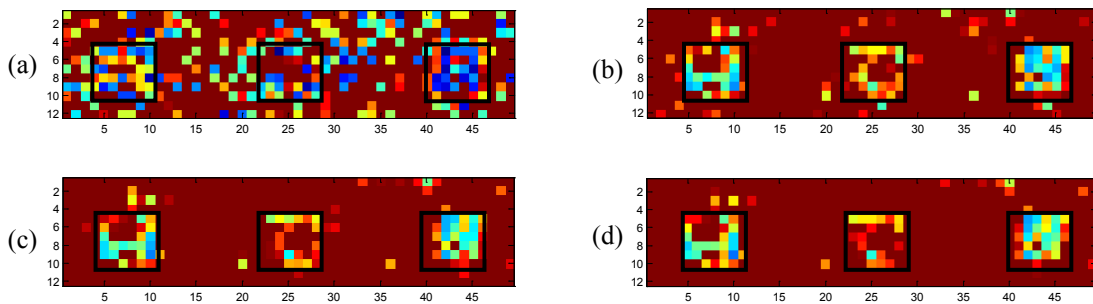


Figure 5: A C-Scan image at the depth of 8 mm (a) and the images averaged in the axial direction by the window sizes of 1 mm (b), 1.5 mm (c) and 2 mm (d). The black boxes indicate the expected defect areas. The scanning step was 5 mm. The colours on the image relate to the echo strength from the fixed depth zone.

### 3.2 Wind turbine blade testing

Figure 6 shows a piece of 14 mm thick wind turbine blade (GFRP) with a 30x30 mm defect measured 10 mm deep from the inner side. It was scanned from the top surface using a step size of 10 mm. Figure 7 shows the C-Scan images at the depth of 4 mm and averaged by the window sizes of 1 mm and 1.5 mm in the axial direction. The defect can be roughly identified but the result is slightly poorer than the previous result on the 8 mm GFRP. This is mainly due to the lower spatial resolution and also the additional plastic laminated layer on the blade surface causing additional attenuation to the ultrasound signal. Thus the SNR is lower and hence the image quality is lower.

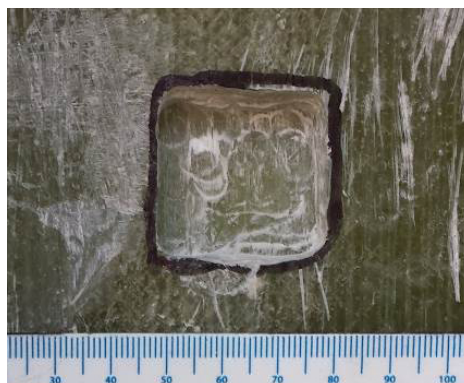


Figure 6: A wind turbine blade sample with a 30x30mm defect (10 mm deep from the bottom).

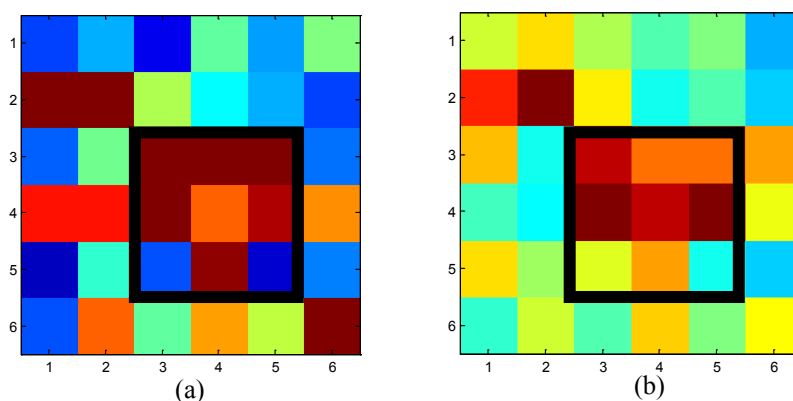


Figure 7: C-Scan images of a piece of wind turbine blade sample (GFRP) at the depth of 4 mm averaged in the axial direction with the window sizes of 1 mm (a) and 1.5 mm (b). The black boxes indicate the expected defect areas. The scanning speed was 10 mm.

## CONCLUSION

This paper has presented a prototype of automated ultrasonic NDT system. The system consists of an ultrasonic pulser-receiver and an automated positioning device which are both connected to a computer. A Matlab software system has been developed to synchronously control the positioning device to position the ultrasound transducer in a 2D area and control the pulser-receiver to collect ultrasound data from each scanning point. The whole system (excluding computer) is about 5 KG and can be affixed on the wind turbine blade surface for an automated 2D scan. It is portable to be carried by an inspector climbing onto the wind turbine blade for in-situ inspection.

The system has been tested on GFRP and wind turbine blade samples. The results showed that defects of 30x30 mm can be easily identified on the C-Scan image averaged over about 1-2 mm in the axial direction of the ultrasound data. Further work will be considered to optimise the system parameters, e.g. ultrasound power, scanning speed and also investigate signal/image processing techniques for a better visualisation on the defect area.

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