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Determination of the Structural Integrity of a Wind Turbine Blade Using Ultrasonic Pulse–Echo Reflectometry

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ABSTRACT

This paper is generally concerned with an analysis of a wind turbine blade using a Non-destructive Evaluation Test (NDT) procedure. The Ultrasonic Pulse-echo Reflectometry was used to estimate the structural composition of the various layers of the wind turbine blade. Estimates of the thickness of gel-coat and glass reinforced plastic (GRP) were obtained by the plots of thirty-six (36) sets of data comprising of seven (7) groups of A-scans using a spreadsheet in Microsoft Excel 2007. These sets of experimental data were obtained from sample sections of gel-coat and glass reinforced plastic (GRP) which were formed by deliberate defects inside. A mathematical model of pulse–echo propagation which is $2d = vt$ was used to determine the thickness variation of the layers for the seven (7) groups of A-scans. From estimates of the thickness of the layers C-scans were designed to determine the thickness variation of the various groups of A-scans. From the comparison of the acoustic impedances of the gel-coat and GRP, it was possible to detect disbonds, delaminations and porosity in the bonded structures of the wind turbine blade.

Keywords: *Structural integrity; Wind turbine blade; Pulse-echo reflectometry; delaminations; disbonds*

1. INTRODUCTION

Non-destructive evaluation (NDE) is a method of testing structures and materials without damaging them in any way. Many industries routinely sue NDE method to access a wide range of products. Many different parameters can be measured by NDE, for example, there are general quality assurance test for structural integrity and the dimensions of an object may be found. NDE techniques are often used specifically to find particular defects in a structure. There is a wide range of NDE methods from simple virtual tests to more sophisticated x-ray tests. Each technique may not be suitable for some applications so care must be taken to ensure that the most appropriate is selected for a particular application. Ultrasonic pulse-echo Reflectometry provides a simple method to estimate the thickness of a wide range of materials both in the laboratory and as parts of engineering structures in fields [1]. This paper is generally concerned with an analysis of a wind turbine blade using ultrasound pulse-echo Reflectometry to estimate the thickness of both the gel-coat and glass reinforced plastic (GRP) which is obtainable by plotting of thirty-six (36) sets of data comprising of seven (7) groups of A-scans. From the A-scans, estimates of the various thickness of the gel-coat and glass reinforced plastic (GRP) were achieved. The estimated thickness was used to determine the presence of disbond in the gel-coat-GRP interface and delamination in the GRP (glass reinforced plastic). The presence of disbond between the gel-coat-GRP interface results in a negative amplitude pulse echo (Z2<Z1), the acoustic impedance of air is less than that of the gel-coat leading to100% reflection. Hence, most of the ultrasound energy is reflected back to the transducer and almost no pulse-echo transmission into the GRP which gives us no back-face echo preventing the estimation of the thickness of the GRP. The difference in arrival times of pulse-echo (2) and pulse-echo (1) helps us to estimate the thickness of the gel-coat.

However, although the method is relatively easy to carry out, there are aspects of the physical technique and supporting calculations that can cause variations of estimation of the required thickness. One of which is the incorrect evaluation of the A-scan. The crux of the problem is that the thickness estimation is based on measurements of a time domain sequence of ultrasonic echoes from a structure that contains several properties [1, 2].

These echoes are prone to vary due to many factors such as surface variability, transducer-test surface coupling, and electronic thermal, shot and quantization noise. To some extent echo variability can be overcome by frequency domain approaches applied to parameterize the echo sequence, although these increases the time of calculation of the thickness and may be of limited application in economical portable test instruments.

This paper explores the pulse-echo reflectometry method for measuring the thickness of gel-coat and GRP through

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the plots of A-scans of the experimental data in spreadsheet format and C-scans to detect disbonds and delaminations in bonded structures of the wind turbine blade [3, 4].

2. METHODOLOGY

Some experimental pulse-echo data in spreadsheet format were obtained from a sample section of gel-coat and GRP, which has been formed with deliberate defects inside. The sample consists of two layers: the top gel-coat layer vary in thickness between 1mm and 3mm. The second layer is GRP and is 4mm in thickness throughout. In order to enhance the estimation of the thickness of the gel-coat and GRP, the material properties were known. There are two types of defects. The first is a disbond between the gel-coat and GRP and the second is a delamination.

A 10MHz center frequency transducer was obtained for the measurements. Due to attenuation in the materials the sample was made thinner than would be found in a real wind turbine blade. It was assumed that the couplant used had no effect on the experimental data [2].

The experimental data in spreadsheet format comprises of thirty-six (36) data arranged from A1-A6, B1-B6, C1-C6, D1-D6, E1-E6 and F1-F6. When carefully selected, form groups of seven (7) distinct data of various A-scans. Hence, each individual group has the same value of estimated thickness. This was achieved using a gel-coat central frequency of 10MHz with a corresponding velocity of 2608m/s. This was chosen because the difference in velocities between the shoe and gel-coat determines the transmission rate of pulse-echo into the wind turbine blade. If the difference in velocities of the shoe and gel-coat is relatively small there will be through transmission of ultrasound energy into the gel-coat. Also, to set the gel-coat into oscillation or vibration thereby sending ultrasound energy into the gel-coat , the difference between the velocities/frequencies of the shoe and gel-coat should be relatively small. This helps to send large amplitude of transmission of ultrasound energy into the gel-coat.

2.1 Procedure

The A-scan comprises of a set of ten data {A1, A2, A3, A4, A5, A6, B1, C1, D1, and D2}. The A-scan is a plot of amplitude voltage of ultrasound signal against time. The principle of pulse-echo propagation can be mathematically modelled as $2d = vt$

where

d = distance travelled by the pulse or thickness of the material medium of propagation.

$v =$ Velocity of material medium

$t =$ Arrival time of pulse

The interest was on estimating the thickness of gel-coat and to achieve this the arrival time of the pulse is denoted as Δt_{gel} which is the time to go through gel-coat twice and v_{gel} is the velocity of gel-coat. The characteristics of the A-scan in figure 1 are as follows ;

1. The first pulse-echo is the top surface reflection.
2. The second pulse-echo propagates through shoe into the gel-coat and reflected from GRP and back to the transducer (twice the thickness of gel-coat).
3. The third pulse-echo is multiple reverberation (has propagated four times through the gel-coat).
4. The fourth pulse is the back-face echo (has propagated through the gel-coat and then back to the transducer) from the GRP-air interface with 100% reflection.

Calculation of Gel-Coat Thickness (Group1)

$$v_{gel} = \frac{distance}{time} = \frac{2 \times thickness\ of\ gel}{\Delta tgel}$$

$$t_{gel} = t_1 - t_2$$

t_1 = Arrival time of pulse echo (1)

t_2 = Arrival time of pulse echo (2)

$\therefore$ Thickness of gel-coat (d_{gel1}) $= \frac{v_{gel} \times \Delta t_{gel}}{2}$

Velocity of gel-coat at 10MHz central frequency

(v_{gel}) = 2608m/s

For $t_1 = 0.45 \times 10^{-6}s$ and $t_2 = 1.99 \times 10^{-6}s$

$$\Delta t_{gel1} = 1.99 \times 10^{-6} - 0.45 \times 10^{-6} = 1.54 \times 10^{-6}s$$

Gel-coat thickness

$$(d_{gel1})\ for\ group\ 1 = \frac{2608 \times 1.54 \times 10^{-6}}{2}$$

$$d_{gel1} = 2.00816mm$$

A-SCAN OF GROUP 1

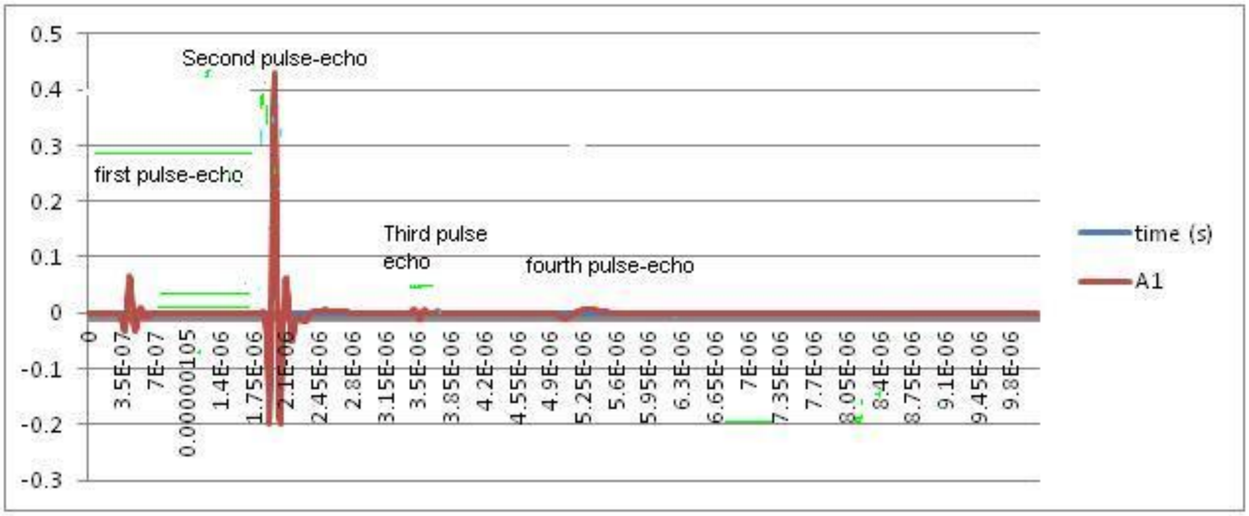

Figure 1. A plot of amplitude against time showing variation of thickness in gel-coat and GRP

Calculation of GRP Thickness for Group1

The thickness of the GRP can be estimated using the procedure above

$$v_{grp} = \frac{distance}{time} = \frac{2 \times thickness\ of\ grp}{\Delta tgrp}$$

$$t_{grp} = t_4 - t_2$$

$t_4 =$ Arrival time of pulse echo (4)

$t_2 =$ Arrival time of pulse echo (2)

$\therefore$ Thickness of gel-coat (d_{grp1}) $= \frac{v_{grp \times} \Delta t_{grp}}{2}$

Velocity of GRP at 10MHz central frequency

$(v_{grp}) = 2603$m/s

For $t_4 = 5.26 \times 10^{-6}s$ and $t_2 = 1.99 \times 10^{-6}s$

$$\Delta t_{grp1} = 5.26 \times 10^{-6} - 1.99 \times 10^{-6} = 3.27 \times 10^{-6}s$$

GRP thickness (d_{grp1}) $for\ group\ 1 = \frac{2608 \times 3.27 \times 10^{-6}}{2}$

$d_{grp1} = 4.255905mm \approx 4.0mm$

The respective A-scans from Group 2 to Group 7 were plotted with Microsoft excel 2007 plotting tools. These A-scans are shown in the figure 2 to figure 7. The respective thickness of gel-coat and GRP were also calculated using the procedure in 2.1.

A-Scan of Group 2

The A-scan is a set of two data {B2, C2}. The characteristics of the A-scan in figure 2 are as follows;

1. The first pulse-echo is the top surface reflection.

2. The second pulse-echo is a disbond in the gel-coat-GRP interface. The pulse is inverted which implies that there is air gap in the internal boundary creating 100% reflection at the interface. Hence, the reflection coefficient is negative $(z_{air} < z_{gel})$. Pulse echo amplitude is higher for disbond and there is no back-face echo.

3. The third pulse-echo is multiple reverberation (has propagated four times through the gel-coat).

A-Scan of Group 3

The A-scan is a set of two data {B3, C3}. The characteristics of the A-scan as seen in figure 3 are as follows;

1. The first pulse-echo is the top surface reflection.

2. The second pulse-echo is a disbond in the gel-coat-GRP interface. The pulse is inverted which implies that there is air gap in the internal boundary creating 100% reflection at the interface. Hence, the reflection coefficient is negative $(z_{air} < z_{gel})$. Pulse-echo amplitude is higher for disbond and there is no back-face echo.

3. The third pulse-echo is multiple reverberation (has propagated four times through the gel-coat).

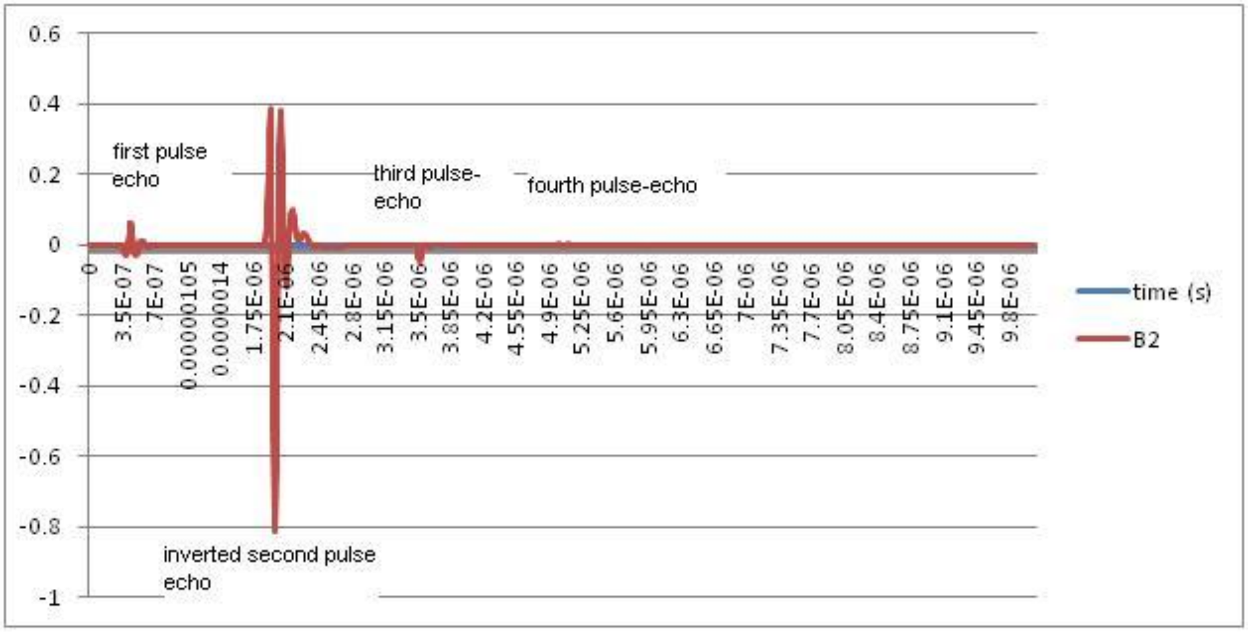

Figure 2. A plot of amplitude against time showing variation of thickness in gel-coat and GRP

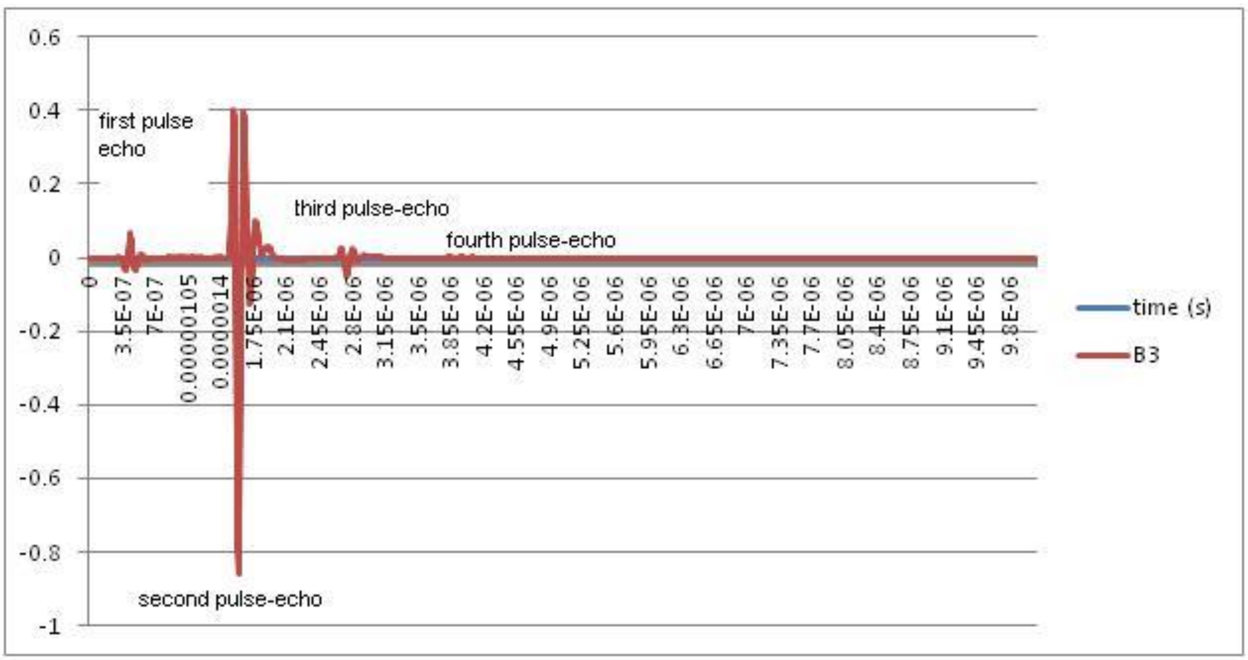

Figure 3. A plot of amplitude against time showing variation of thickness in gel-coat and GRP

The thickness of the GRP can't be estimated because pulse-echo (2) is inverted, the ultrasound signal is 100% reflected due to disbond in the gel-coat-GRP interface.

Note: Any defect at the top layer will mask out any other potential problem below it.

The arrival time is dependent on the gel-coat thickness and presence of delamination. In this case, there is no back-face echo and the thickness of the gel-coat is small, there is no delamination in the GRP but there is loss of signal in the gel-coat which results to reduction in arrival time.

A-Scan of Group 4

The A-scan above is a set of (seven) data {B4, B5, B6, C6, D6, E6, and F6}. The characteristics of the A-scan as seen in figure 4 are as follows:

1. The first pulse-echo is the top surface reflection.

2. The second pulse-echo propagates through shoe into the gel-coat and reflected from GRP and back to the transducer (twice the thickness of gel-coat).

3. The third pulse-echo is multiple reverberation (has propagated four times through the gel-coat).

4. The fourth pulse is the back-face echo (has propagated through the gel-coat and then back to the transducer) from the GRP-air interface with 100% reflection.

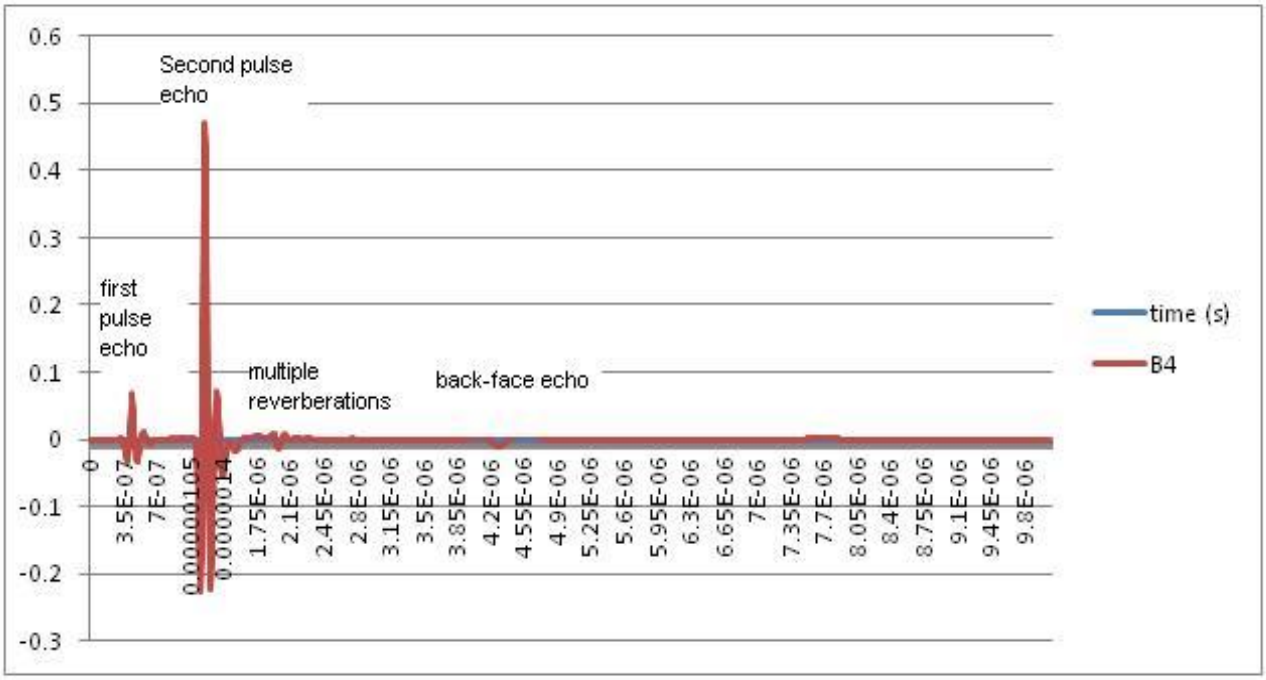

Figure 4. A plot of amplitude against time showing variation of thickness in gel-coat and GRP

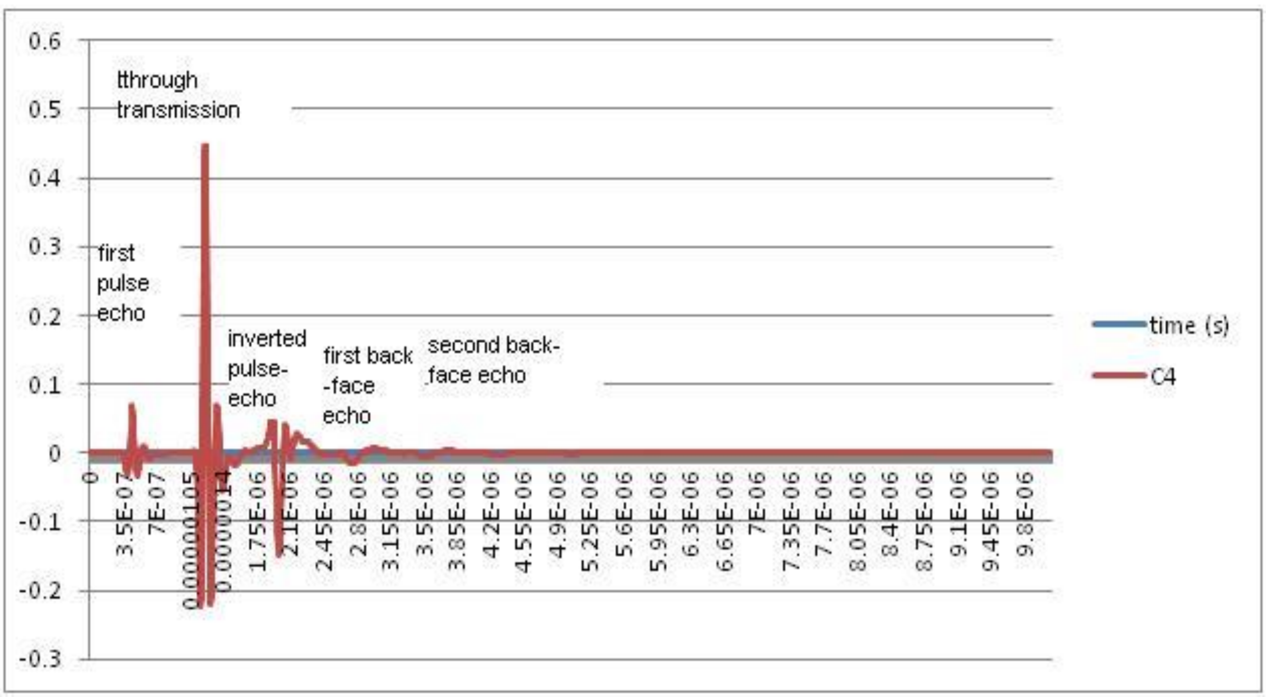

Figure 5. A plot of amplitude against time showing variation of thickness in gel-coat and GRP

A-Scan of Group 5

The A-scan is a set of six data {C4, C5, E2, E3, E4, and E5}. The characteristics of the A-scan in figure 5 are as follows;

1. The first pulse-echo is the top surface reflection.

2. The second pulse-echo propagates through shoe into the gel-coat and reflected from GRP and back to the transducer (twice the thickness of gel-coat).

3. The third pulse-echo is much larger due to constructive interference of second echo in the gel-coat (multiple reverberations) and first back-face echo (delamination) in the GRP. Therefore the GRP is very thin. There is an air-gap in the GRP giving us an inverted pulse $(Z_{GRP} > Z_{AIR})$. The amplitude of the reflected pulse from delamination in GRP multiplies with the reverberation in gel-coat which is happening at the same time.

4. This is the first back-face echo as a result of delamination in the GRP.

5. The fifth pulse is the second back-face echo (has propagated through the gel-coat and then back to the transducer) from the GRP-air interface with 100% reflection.

The thickness of the GRP is approximately 1mm thick which explains the fact that the GRP is very thin and the velocity of the GRP becomes very small as well.

A-Scan of Group 6

The A-scan is a set of three data {D3, D4 and D5}. The characteristics of the A-scan in figure 6 are as follows;

1. The first pulse-echo is the top surface reflection.

2. The second pulse-echo is a disbond in the gel-coat-GRP interface. The pulse is inverted which implies that there is air gap in the internal boundary creating 100% reflection at the interface. Hence, the reflection coefficient is negative $(z_{air} < z_{gel})$. Pulse echo amplitude is higher for disbond and there is no back-face echo.

The thickness of the GRP can't be estimated because pulse-echo (2) is inverted, most of the ultrasound signals are 100% reflected due to disbond in the gel-coat-GRP interface.

Note that any defect at the top layer will mask out any other potential problem below it.
The arrival time is dependent on the gel-coat thickness and presence of delamination. In this case, there is no back-face echo and the thickness of the gel-coat is small, there is no delamination in the GRP but there is loss of signal in the gel-coat which results to reduction in arrival time [4 -6].

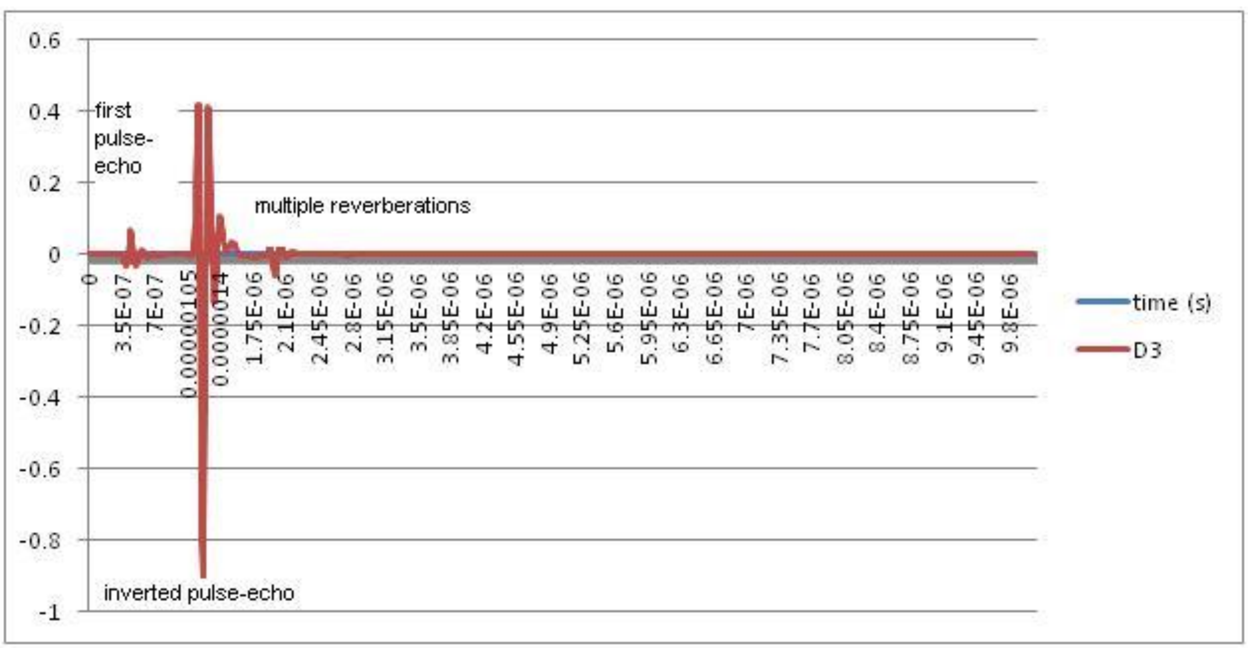

Figure 6. A plot of amplitude against time showing variation of thickness in gel-coat and GRP

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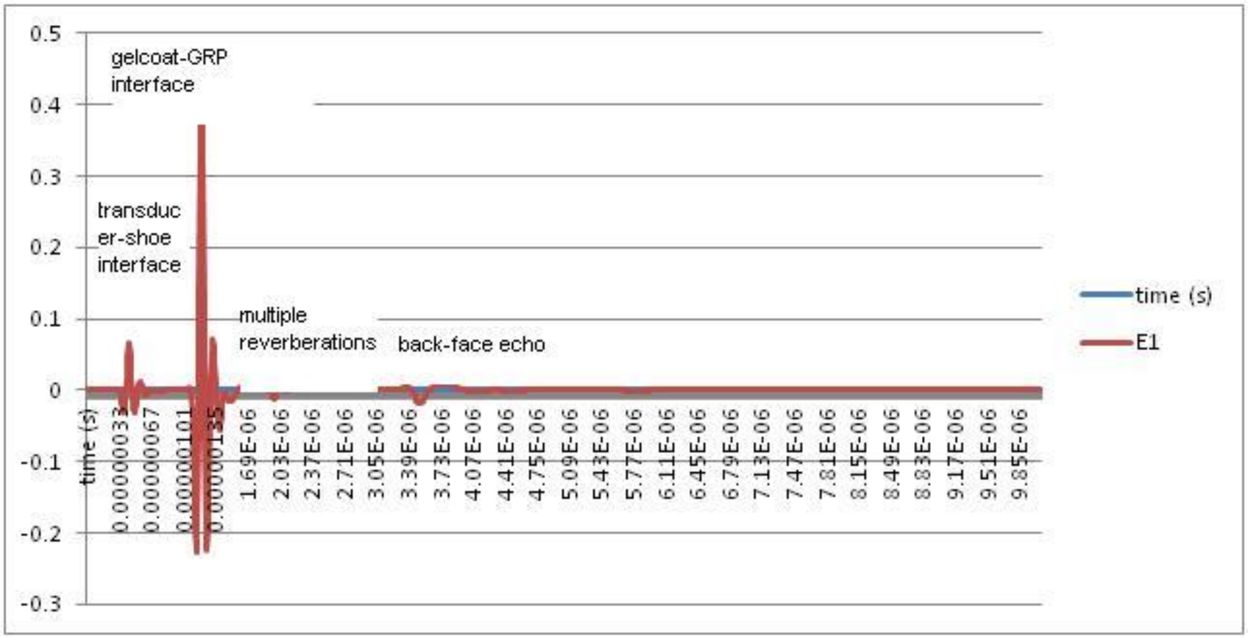


Figure 7. A plot of amplitude against time showing variation of thickness in gel-coat and GRP

3. DISCUSSIONS

For all seven (7) groups of thirty-six sets of experimental data the A-scans possess small amplitudes for the first pulse-echoes which explains the fact that the shoe and gel-coat are made of similar materials. For an ideal case in Group 1 after the gel-coat-GRP interface there is attenuation in the GRP as the signal travels through it. Hence, it acts effectively as a low pass filter because attenuation increases with frequency and propagation distance. The fast-Fourier transform of the back-face echo decays nicely with time reducing the value of the centre frequency [7, 8].

The gel-coat varies between 1mm-3mm and this can be seen from the C-scan in figure 8. C-scan is the data representation technique used in the industry and is produced from the A-scan data. It was used to detect disbonds and estimate the material properties of the wind turbine blade. Group 2 had a greater thickness than Group 1 but only occur twice in the C-scan (figure 8) but Group 1 occurs more frequently in the C-scan and has the second highest thickness value which is an approximate of Group 2 (2mm).

It was observed that the gel-coat is thinner in Group 4 and Group 7 (1.00408mm), followed by Group 5 and Group 6 (1.01712mm) which are thinner than Group 3 (1.15264mm). Group 3 (1.15264mm) is thinner than Group 1 and Group 2 ($\approx 2mm$).

There were no disbonds in Group 1, Group 4, Group 5 and Group 7. The groups with thinner gel-coats generate multiple reverberated pulse-echoes which are very close to the second pulse echo. There is back-face echo which helps to estimate the thickness of the GRP.

Group 2, Group 3 and Group 6 have disbonds (air-gap) at the gel-coat –GRP interface which gives 100% reflection preventing the propagation of the signal in the GRP. Hence, the thickness of the GRP cannot be estimated which is represented here as 0mm.

For Group 1, the GRP thickness is 4.0mm which implies that there is no delamination in the GRP.

For Group 4, the GRP thickness is 4mm which implies that there is no delamination in the GRP.

For Group 5, the GRP thickness is $\approx 1mm$ which is very thin and indicates the presence of delamination in the GRP.

For Group 6, the GRP thickness is $\approx 3.3mm$ not very thin and indicates the presence of delamination in the GRP. These can be seen from figure 9.

4. RESULTS

4.1 Effect of Porosity

Porosity is small air content in cured polymers, ceramics, and composite materials. Its presence reduces mechanical performance as a result of stress concentrations [3, 9]. In this report, if there had been porosity in the material it would have been located in the GRP usually spread throughout the layer or in a line along the fibers. Porosity in general increases attenuation due to scattering therefore its occurrence results in a decrease in amplitude of the back-face echo.

C-Scan Showing Variation of Gel-Coat Thickness

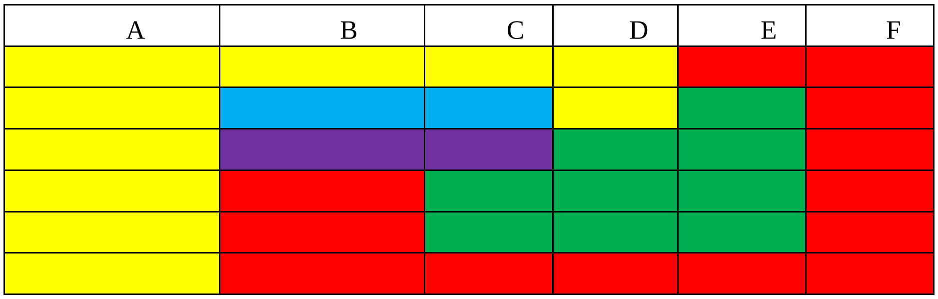
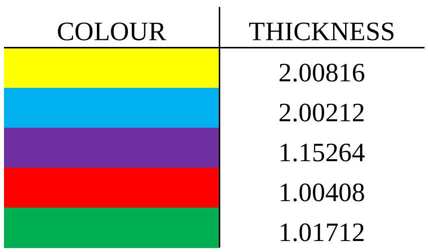


Figure 8. C-scan showing variation of gel-coat thickness



Tab.1: Estimated thickness of gel-coat for thirty-six (36) sets of data

A	B	C	D	E	F
2.00816	2.00816	2.00816	2.00816	1.00408	1.00408
2.00816	2.0212	2.0212	2.00816	1.01712	1.00408
2.00816	1.15264	1.15264	1.01712	1.01712	1.00408
2.00816	1.00408	1.01712	1.01712	1.01712	1.00408
2.00816	1.00408	1.01712	1.01712	1.01712	1.00408
2.00816	1.00408	1.00408	1.00408	1.00408	1.00408

C-Scan Showing Variation of Grp Thickness

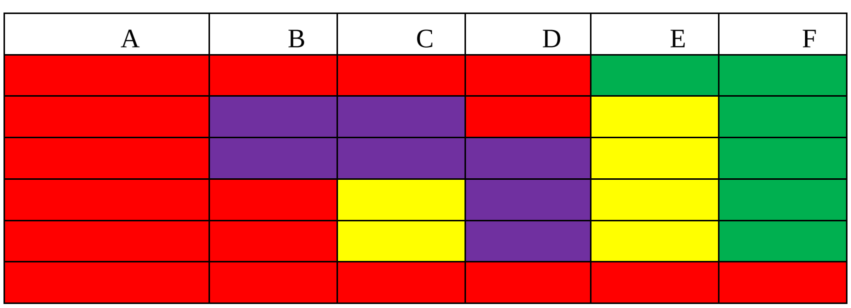
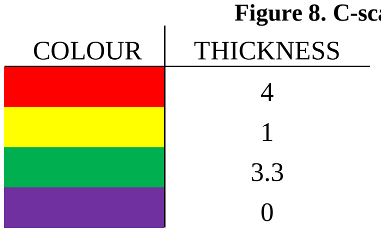


Figure 8. C-scan showing variation of GRP thickness



Tab.2: Estimated thickness of GRP for thirty-six (36) sets of data

A	B	C	D	E	F
4.0	4.0	4.0	4.0	3.3	3.3
4.0	0.0	0.0	4.0	1.0	3.3
4.0	0.0	0.0	0.0	1.0	3.3
4.0	4.0	1.0	0.0	1.0	3.3
4.0	4.0	1.0	0.0	1.0	3.3
4.0	4.0	4.0	4.0	4.0	4.0

5. CONCLUSION

A change in the center frequency of the transducer will lead to a possible change in the thickness of the material under test which will lead to variation in the results. The features of the ultrasonic wave (velocity, attenuation) were used to characterize materials composition, structure, elastic properties, density and geometry in complex materials [3, 4]. Ultrasonic pulse-echo reflectometry helps us to estimate the thickness of gel-coat and GRP, giving their various velocities of propagation. The ultrasonic pulse-echo mathematical model $2d = vt$ was used to estimate the thickness of the gel-coat and GRP. The experimental data forms seven (7) groups of A-scans with various properties. With a good understanding of the A-scans the thickness of the gel-coat and GRP was obtained. With these results, plots of two C-scans were obtained. The first shows the variation of the thickness of the gel-coat while the second shows the variation of the thickness of the GRP.

From proper analysis of the A-scans and C-scans the presence of disbonds and delaminations in the gel-coat and GRP were detected. The effect of porosity was also stated as it reduces the amplitude of the back-face echo.

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