



Ultrasonic Methods

5 MHz Ultrasonic Attenuation Coefficient Determination and Delay Law Calculations

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Abstract

A detailed comparison of attenuation in different materials was carried out, detailing how frequency, wave length and grain structures can effect ultrasonic sound loss in different materials. For all four sample pieces tested there was varying sound losses, with some formulae, calculation and graphical analysis it was found that the composite lost the most decibels. Research proved that the non-homogeneous arrangement of the composite was the cause of the loss of decibels in the sound wave, with sound scattering and absorbing within the weaves. The relationships found and results displayed detail information that should be considered when attempting to find a defect within similar materials.

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3. Literature Review

3.1 Ultrasonic Testing Basics

Ultrasonic testing techniques are widely used for many tasks in NDT such as detecting internal surface cracks in materials and structures, as well as gathering information on material depth and continuity of the material. The techniques of ultrasound can be used for metallic, non-metallic and for composite materials, although the testing method will vary slightly between materials.

The basic principle of ultrasonic testing in NDT is creating an elastic sound wave with a piezoelectric crystal transducer and then propagating this sound wave through a material or structure. Here to create this an alternating voltage will be applied to a piezoelectric crystal which will cause the crystal to expand and contract thus sending out a compression sound wave (Vernon John – an introduction to engineering materials 4th edition p546). The transducer (piezoelectric crystal) will also act as a receiver of the signal sent, this set up is known as 'single crystal'. A set up where two transducers are used one to emit a signal and one to receive a signal is known as a 'twin crystal' set up. Twin crystal probes are generally needed for short-range operations (Practical non-destructive testing pg 93-110), this report will predominately be using single crystal probes.

When the wave path meets a discontinuity (i.e. a crack), part of the energy from the original wave will be reflected, back from the surface of the crack to the probe. This reflected wave signal from the crack is then transformed into an electrical signal by the transducer when it reaches back to the probe, creating what is known as an 'A- scan' to be displayed on the screen of ultrasonic testing equipment. In figure... on the following page the reflected signal strength (amplitude), is displayed on the Y-axis and time on the X-axis, this is displaying the signal from generation to when an echo was received. There will be a defined velocity as to which the sound wave is traveling at per given material, therefore if the speed of the sound wave and time which it takes is known as in figure.. we can work out the distance a possible crack could be from the surface $Distance = Speed * Time$. (www.nde-ed.org, Ultrasonics, 01).

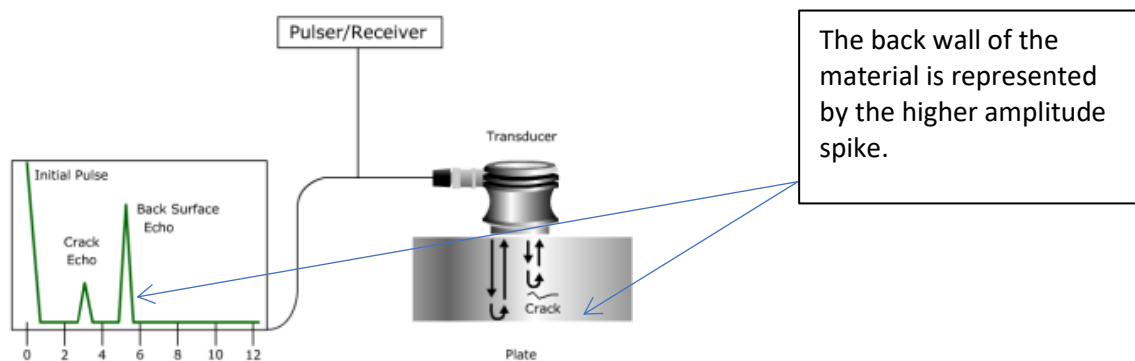


Figure 1 Ultrasonic testing set up

The probe has three main tasks, to protect the user from electric shock, to protect the crystal from mechanical damage, and to make the crystal transducer more suitable for the job (B. Raj, Practical Non-Destructive Testing, 2007).

The transducer will create vibrations that pass through a material at different time intervals, this process will be referred to as acoustics. Acoustic sound waves used in NDT will focus on particles containing groups of atoms moving in unison to produce a mechanical wave of vibration. The wave

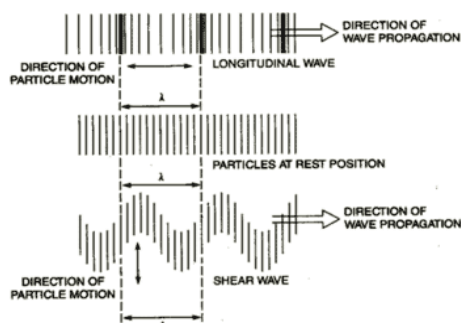


Figure 2 Shear wave

sent from the probe will initially be a compression (longitudinal) wave, meaning that the sound will travel in a straight-line due to the molecules in the air being compressed against one another and moving forward due to this compression. Longitudinal and shear waves are the two

most common, shear wave (transverse wave) particles will act a right angle to the direction of wave propagation and will act like a sine wave as the figure above displays. These shear waves are needed in certain inspection situations where a longitudinal wave may not be the best approach to finding a defect (www.nde-ed.org, Wave propagation, 2017).

Information will be received from both single and twin crystal probes in the form of an A-scan (amplitude scan), as seen in the figure above. In more complex equipment than is being used for this report, these A-scans can be used to produce a B-scan, or as the medical world refers to it a brightness scan which details peaks of amplitude as varying colours to give information.

3.2 Speed of Sound in Materials

When sound moves through a material it does so by means of the material itself vibrating, where effectively the molecules over here will crash into their neighbours which in turn collide with molecules further on still (PRETOR-PINEY, 2010). The speed of sound in materials (within controlled temperature environments) will vary due to three main factors. The most important being what type of wave is being produced, and the other two being the density and Young's modulus properties of the material.

We will consider the two most common forms of wave, the longitudinal sound wave (compression) travel at roughly twice the speed as shear sound waves, one reason for this being that as the shear wave is moving at right angles, therefore, the particles are less compressible than the longitudinal wave, meaning that it will gain less momentum. Young's modulus of elasticity describes how a material holds its molecular structure, and how these molecules want to return to its original position when a force is applied to it, this means that when a sound wave propagates through a high modulus of elasticity material the molecules will attempt to hold their position due to their attraction to one another which will cause higher vibrations in the molecules. Density affects the speed of sound in materials due to the denser a material the more closely together the molecules will be packed together, therefore with closely packed molecules in a material the reaction mentioned of molecules crashing into one another can happen at a faster rate. If we view this in a practical sense steel has a speed of sound velocity of 5960m/s, whereas air at 20°C has 343m/s, the reason being that steel can vibrate at higher speeds than the air due to the molecules having stronger attraction and being more closely packed together than air (PRETOR-PINEY, 2010).

3.3 Attenuation & Dissipation

Attenuation can simply be described as the loss of amplitude received on the testing machine per cycle (Blitz, 1996). When sound propagates through materials there are two predominant physical processes which will weaken its propagation, these are scattering and absorption. Scattering describes how the sound is reflected in undesired directions possibly due to the material being inconsistent and containing inclusions or pores. Absorption is when sound energy is converted into other forms of energy, such as heat energy due to reasons such as internal friction between the sound wave and the material. These two physical losses combined are what is known as attenuation (B. Raj, Practical Non-Destructive Testing, 2007).

3.3.1 Couplant & Acoustic impedance

The need for a couplant between the probe and the test piece will refer to acoustic impedance matching. Acoustic impedance defines what proportion of sound energy will transmit to the second medium and what proportion will be reflected to the probe, i.e. from the probe to the test piece with couplant being the first medium it encounters. Solids have high acoustic impedance values (reflect less energy) in comparison to gases (air) which have low values (reflect more energy), with this being the case it would stand to reason that if we had no medium between the probe and the test piece the sound wave would have to travel through air to reach the test piece which will result in most of the sound wave being reflected before it has reached the test piece. To control this loss of energy couplant is used between the probe and test piece which can be water, oil, gel or a paste, all of which liquids have a closer acoustic impedance to solids than gas. The general purpose is to have a medium with a closer acoustic impedance to a solid material so more of the sound wave can be transmitted.

3.4 Probe bandwidth

Although the probe may be labelled as 5MHz frequency probe, it will not generate a pure frequency of only 5MHz during the pulse, but instead a band of frequencies known as the bandwidth of the transducer (Frequency being defined as the number of vibrations which an individual particle makes per unit of time (Cambridge, 2000)). This will occur because of the beam diverging as it leaves the probe and the central point becoming less intense.

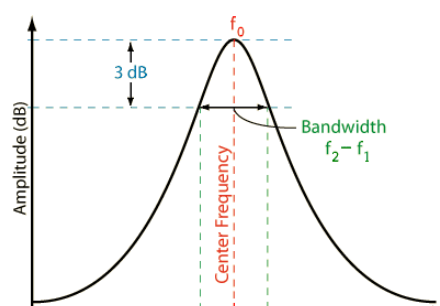
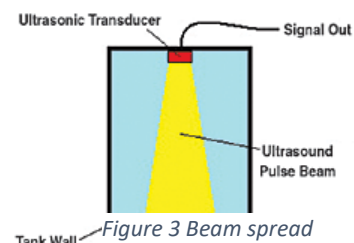


Figure 4 Probe bandwidth

The point f_0 in the figure to the left would be the labelled frequency of the probe (i.e. 5MHz). The bandwidth displayed are points taken from a reduced percentage of amplitude such as – 30% (as displayed here), or -50% of the amplitude can be used to describe bandwidth

(here narrow bandwidth).

What determines this bandwidth is down to the thickness of the crystal and its electric properties, but the most influential factor is due to impedance matching the backing material set behind the crystal (www.nde-ed.org, Ultrasonics, 01)

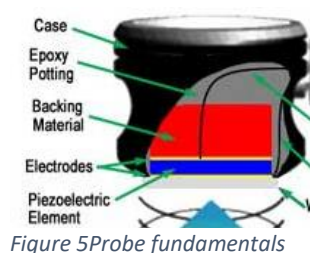


Figure 5 Probe fundamentals

If the backing material has a similar impedance value to the crystal it will keep the waves reflected onto the backing material in phase with one another, creating a wider bandwidth. This wider bandwidth will not penetrate as deep as the narrow bandwidth due to waves being damped,

but will give good resolution in short distances as the waves are all in phase. Therefore, vice a versa if a material with less damping properties is used in the probe the waves will be reflected out of phase but will be able to penetrate greater distances as they are not damped.

3.5 Near-field Far field

Near the transducer multiple soundwaves are being produced as the crystal is vibrating, this results in constructive and destructive waveforms propagating causing the sound field here to be unpredictable with fluctuations from various sound waves being in phase and out of phase with one another, this area is known as the Near-Field. Further away from the transducer the same waveforms begin to form a more unison path in comparison to how they were behaving in the Near-Field, here the waves are now forming a pattern which is originating from the centre of the transducer.

In the near field there will be random amplitude variations displayed on the UT display unit due to the waveforms being constructive, destructive and at different points out of phase. For this reason, we will aim to test and take readings from the Far-Field as the sound wave here is more predictable and at its maximum strength which will result in the best chance of detecting a flaw and true results.

The Near-Field can be calculated using the following equation;

$$Near\ field = \frac{D^2}{4\lambda}$$

$D = \text{Crystal diameter}$

$\lambda = \text{Wave length } (\lambda = \frac{\text{Velocity}}{\text{Transducer frequency}})$

This calculation will give a distance at which the near field is acting to give an indication of where to avoid taken readings from.

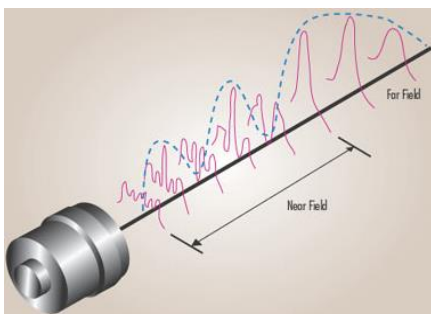


Figure 6 Near-Field Far-Field

4. Introduction & Equipment

Four materials were given to be tested for their attenuation coefficient values using time of flight methods. These were a mild steel step wedge, mild steel block with side drilled holes, a composite material and an unknown sample only described as being non-ferrous. The first task would be to try to define the unknown sample material, then proceed to work out the attenuation coefficients of the samples. It was expected that the composite sample would need more attention paid to it as it was predicted that it would be difficult to determine a second back wall echo due to the layered weaves in the composite distorting the ultrasound. Once measurements had been taken, it would be able to graph the data recorded in excel to try to draw some conclusions from the testing procedure, material behaviours and possibly how a defect can affect readings.

A series of problems were also solved involving phased array systems which can be found in the appendix.

Apparatus

- Zero-degree 5MHz single crystal probe
- Digital Vernier height gauge
- Digital Vernier Calliper
- Mass Scales (see appendix 2)
- Silver Wing – Ultrasonic Testing Machine (Serial numbers 1004104, 1004431)
- Coupling - Tap Water

5. Measurements & Graphs

5.1 Defining the unknown sample

A Basic hardness test was run (shown in appendix 1), here a steel ball bearing was dropped down a one-meter high tube to see how it would absorb the energy of the bounce in relation to mild steel.

The idea being that if the ball bearing had no bounce it was a very soft metal, and vice versa many bounces would indicate a harder more ductile metal. The ball bearing bounced 7 times, whereas the mild steel bounced 4 times, therefore we know the sample is a harder material than the mild steel.

Next density was calculated by weighing and measuring the sample;

Weight: 382.9 grams with validated scales (see appendix 2)

Volume (cm³) $l * w * h$ 11.81 x 5.61 x 1.35 = 89.21cm³

$$\rho = \frac{\text{mass}}{\text{volume}} \qquad \frac{382.9}{89.21} = 4.292 \text{ g/cm}^3$$

If we look into material densities we can see that Titanium can range from 4.37 g/cm³ to 4.84 g/cm³ (www.azom.com, 2017), Indicating that although our density does not fall directly in the region it is very close to it, and the visual characteristics have closer resemblance to the titanium than the closest relatives on the density chart.

A final test was run on the unknown sample using the UT equipment and a basic time of flight calculation knowing that; $Velocity = \frac{Distance}{Time}$. We had determined that the depth of the material was 1.35cm, we now adjusted the velocity on the UT machine until a measurement of depth reading arrived at 1.35cm, the velocity this was found at was 6050 $\frac{m}{s}$. It was found that the speed of sound in Titanium was 6070 from online sources (www.rfcafe.com, 2017) (www.nde-ed.org, Ultrasonics, 01).

It was agreed upon from the tests that the unknown sample was titanium, although the results did not match up exactly to any of the table data these slight discrepancies in values in *Density* and *Velocity* were just put down to variations due to alloying elements changing the properties slightly.

5.2 Testing Procedure for samples

To try to get an overall picture of what was happening in the sample pieces, and whether there would be any differences in the attenuation at different sections in the samples the recordings for the first test were spaced out evenly along the sample. The other two tests would be taking randomly located readings along the samples, then measuring the attenuation from these samples.

Titanium

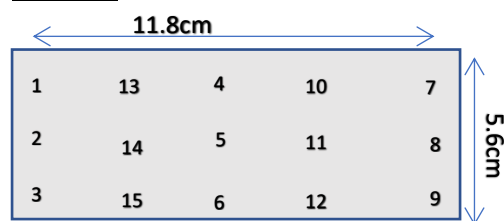
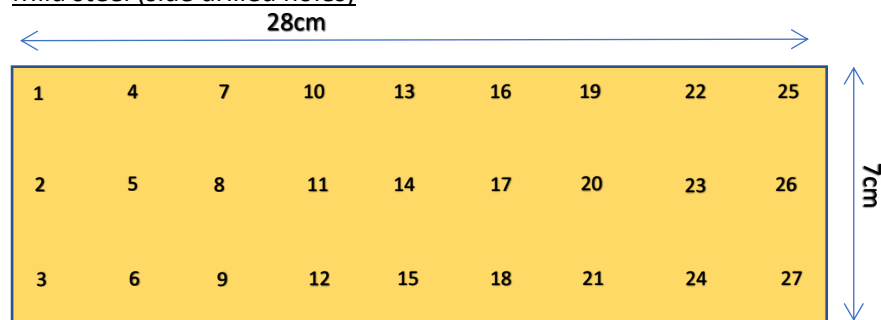
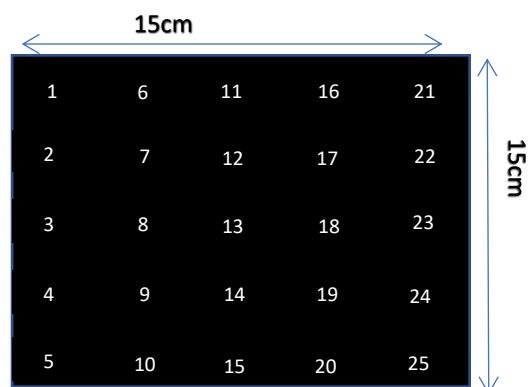


Figure 7 Test one procedures

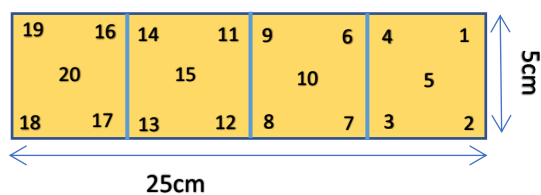
Mild steel (side drilled holes)



Carbon fibre



Steel step wedge



5.3 Measuring Attenuation in the samples

To measure the attenuation in the samples back wall echo heights were recorded from the UT screen as a percentage (fig.) then compared against one another to determine their rate of decay.

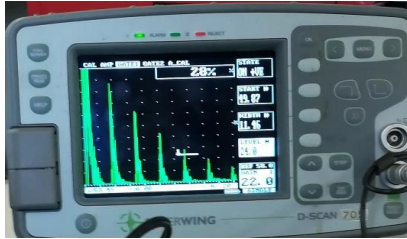


Figure 8 Measuring amplitude peaks

The attenuation coefficient describes the loss of decibels per mm travelled $\left(\frac{dB}{mm}\right)$ of the pulse between the front and back walls of the material.

We use the following equation below (which is a form of the decibel scale), to give the number of decibels lost per millimetre in sound wave travelling between the material front and back walls.

$$\alpha \left(\frac{dB}{mm} \right) = \left(\frac{20}{2 * thickness} * LOG \left(\frac{Echo \text{ final percentage}}{Echo \text{ initial percentage}} \right) \right)$$

This equation will give a value of sound loss in *Decibels lost per millimeter*. Decibels refers to a measurement of sound with 0 being what the threshold of human hearing can detect, i.e. if the equation will give a value of give 1 decibel we have lost 1 times more intense than the threshold of human hearing (Cambridge, 2000). The human ear can detect sound ranging from 0dB to 130Db, in terms of ultrasonic transducers used in NDT and this experiment, we will be looking at small losses of sound intensity.

To take accurate readings the from the screen for back wall percentage heights, the screen was frozen and the gate (which records percentage) moved over the top of each echo being recorded to take an accurate percentage reading ensuring that the probe did not move between back wall echo readings.

To get the attenuation in the carbon fiber an initial calculation was needed to convert a difference in gain used between two back wall heights recorded. This was due to the first initial back wall (A_1) being so much larger than the second back wall (A_2), that it meant that the gain had to be adjusted on the UT machine to take a reading of the second back wall. The reason for this second back wall being so much smaller than the initial was because of the sound scattering and being absorbed so much between the different layers of weave in the composite as the sound pulse travels between the back walls for the second time.

To scale the A_2 up in relation to A_1 we first find the gain difference, we can then follow the next steps;

$$-20 = 20 \log_{10}(\text{scaling factor})$$

Rearranged for the scaling factor by taking the inverse log

$$10^{-\frac{20}{20}} = 0.1$$

Therefore we now have a scaling factor of 0.1 to multiply the back wall height of echo 2 by

E1	E2	Gain 1	Gain 2	Gain difference	E2 scaling factor	E2 scaled	Attenuation $\frac{20}{2 * \text{thickness}} * \text{Log} \left(\frac{\text{E2 scaled}}{\text{E1}} \right)$
72%	22%	55	75	-20	0.1	2.2	-1.83 (dB/mm)

The original plan for test one of the carbon fibre was to take 25 readings evenly spaced along the $15\text{cm} * 15\text{cm}$ board, as was mentioned in section 3.2. This proved to be very difficult due to the scattering and absorption going on between different sections of the board, with many points across the board producing readings that would indicate we were testing in the near field due to sound being reflected from the first layer of weave rather than the back-wall echo which we were looking for. With this problem encountered it was decided to only take 6 of the most satisfying readings from the sample, these were readings that gave a clear back wall each 1 and 2 as opposed to other readings which were distorted.

6. Results, Graphs & Calculations

The results taken from testing were recorded in spreadsheets and graphically plotted. Test one displays the positioned readings, where test two and three display randomly position recordings.

4.1 Test One

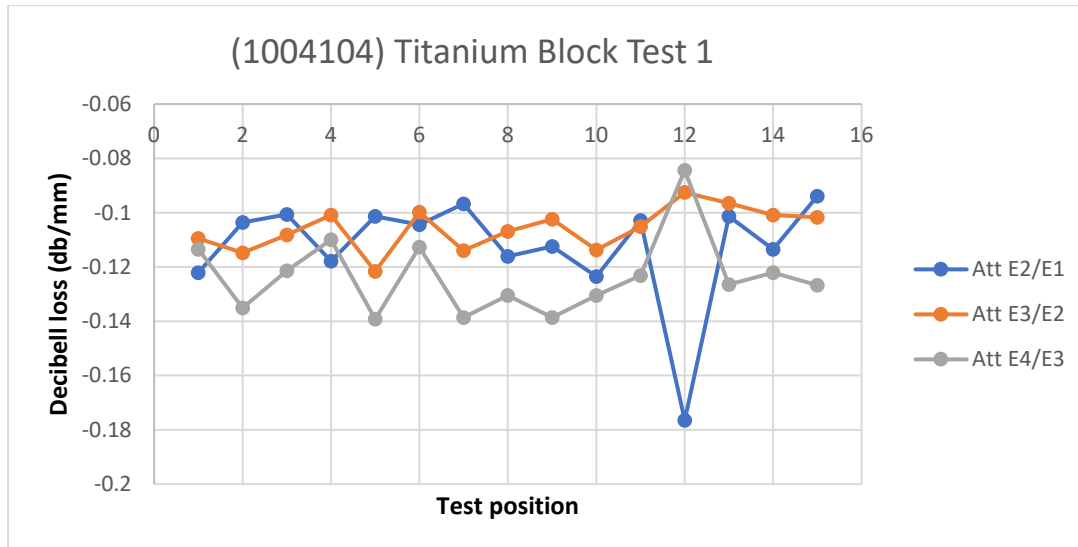


Figure 9 Titanium test one results

In the graph above we can see that sound wave loss in titanium varies from -0.08 to -0.18. It is also clear that at point 12 in the scan (see section 5.2) there was an initial loss between the second and first back wall, then between the third and second and the fourth and third this loss decreased above what would be the standard deviation. This could indicate one of three things; that we are looking at a defect within the sample, a region of discontinuity in the material structure or an operator error.

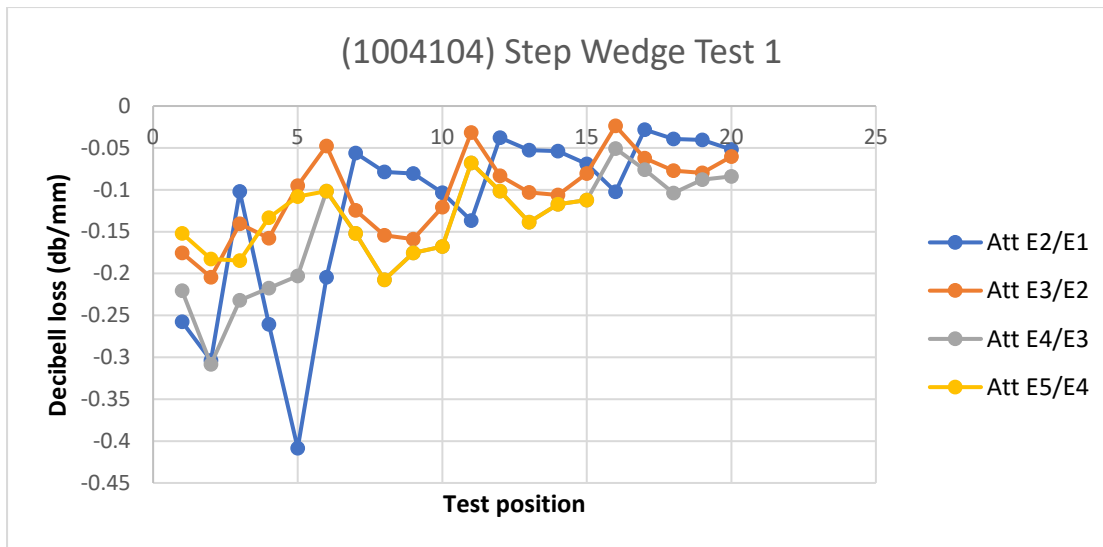


Figure 10 Step wedge test one results

We can see in the 0 – 5 positions of the step wedge the results lack the same correlation to what is displayed between results 10 – 20, especially in the first loss between the second and first second back wall echoes (Att E2/E1). A likely cause for this is that as we are looking to test a piece with a back wall of just 5mm is that readings have been taken from the Near-Field (see section 3.5). We can calculate the near field distance with the following equations;

$$\text{Crystal diameter (1004104)} = 9\text{mm}$$

$$\lambda = \frac{5960}{5 \times 10^6} = 1.192 \times 10^{-3} \text{Metres}$$

$$\text{Near field} = \frac{D^2}{4\lambda}$$

$$\frac{((9 \times 10^{-3})^2)}{(4 \times (1.192 \times 10^{-3}))} = 0.017 \text{Meters}$$

This gives our probe a near field distance of 17mm. Meaning that during readings of the first 3 steps we were testing within the near field. This calculation justifies the graph above as it shows the further we are moving away from the near field the closer the correlation between the attenuation losses.

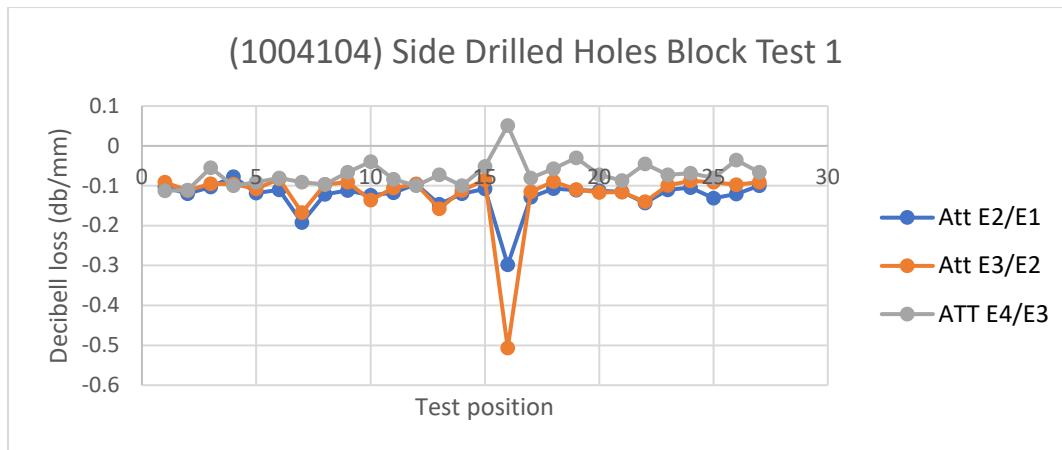


Figure 11 Side drilled holes test one results

The mild steel block with side drilled holes graph above represents test one, here readings were taken evenly spaced out over the block (see section 5.2). This meant that two of the readings ended up being over the side-drilled holes, which in effect gave wide variation to the readings for the average. We can see from the graph that the readings over the side-drilled holes have been at position 7 and 16 which has caused a negative spike in the graph at position 7 and a large initial loss of sound energy at point 16. The reason the side-drilled holes have caused these reactions is because some of the sound energy is absorbed within the hole during the measures of attenuation. If we were to ignore these points on the graph of the side-drilled holes (see appendix 3), the actual attenuation losses in the mild steel block would be like that of the titanium and parts of the step wedge out of the near field. During the random position sampling in test two, these hole positions will be avoided, and random samples taken around them.

In section 1.4 we saw how the frequency of the sound wave will not simply be what the probe is listed as. As the beam starts to diverge it will cause a range of frequencies known as the + & - *dB range*. In deeper components like this mild steel block there will be more beam divergence occurring. This will cause a loss of amplitude as the parts of the beam which is diverged will not return to the probe, instead they will reverberate through the block. We will acknowledge that this loss is happening, and that the loss was not purely attenuation, but ignore it in analysis as the loss will be uniform throughout the block (see appendix 3).

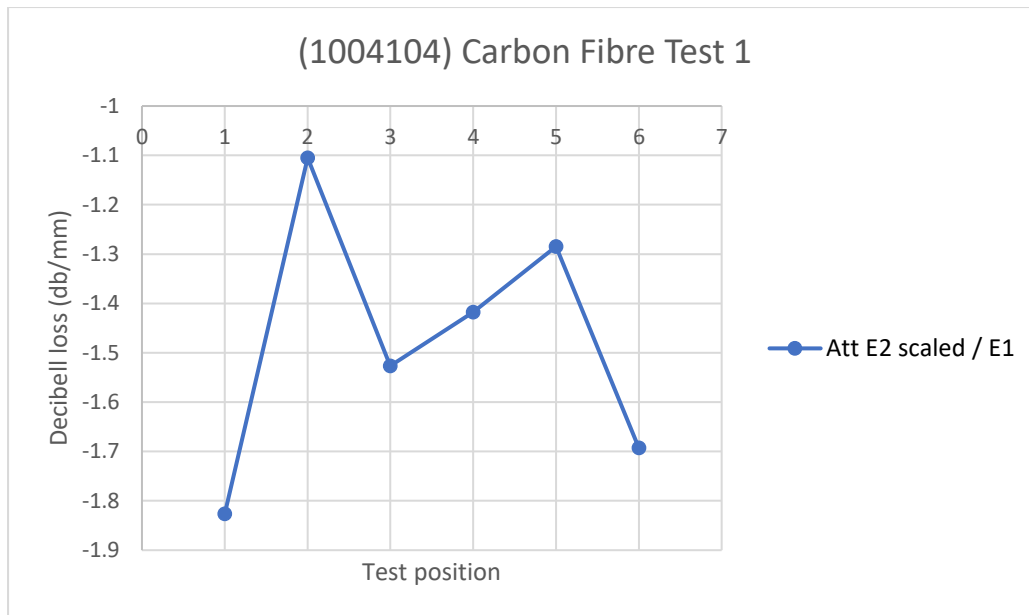


Figure 12 Carbon fiber test one results

The Carbon Fiber graph above shows greater amounts of loss in relation to the other three test samples. This test was originally planned to have data recorded at set intervals (section 5.2), but problems were encountered here such as some positions early in the testing giving amplitude high spikes before reaching the back-wall echo, and generally showing no consistency between recordings. The weave pattern of the carbon fibre was unknown, but what was apparent was that the sound wave at points was reflecting at a high percentage back from plies before the back wall, as well as the weave absorbing more sound in comparison to the metallic samples. All of this generally led to very few positions on the carbon fibre board where legitimate readings could be taken from.

6.2 Test Two

Using the same (1004104) UT machine the testing was repeated on the samples, this time the position of the recordings was taken randomly. The only two exceptions to the probe recording positions being random were the on the mild steel block with side drilled holes the side drilled holes would be avoided, and on the carbon fibre again only the readings where a clear back wall echo can be seen were taken.

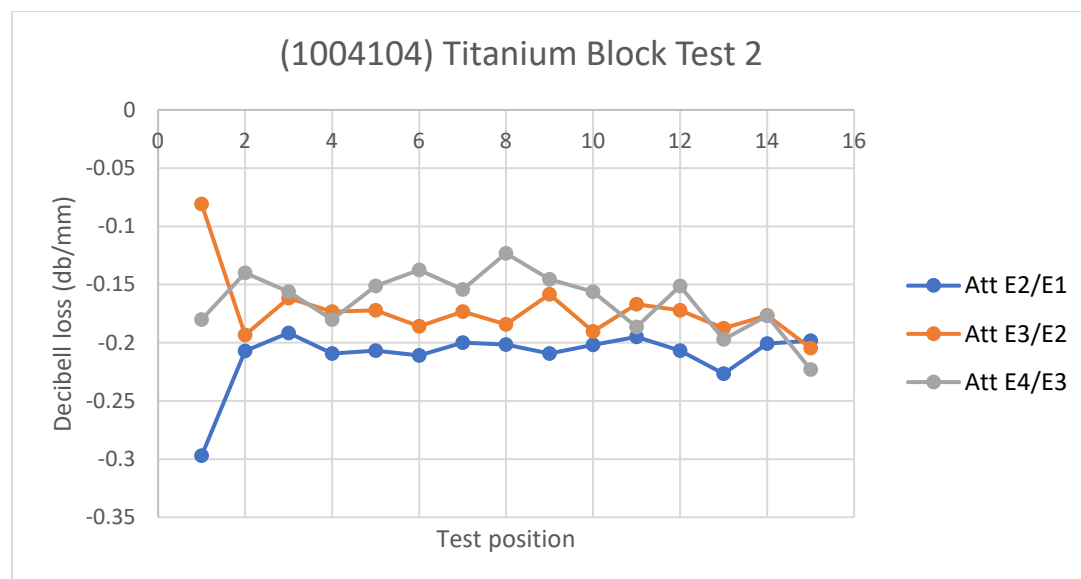


Figure 13 Titanium test 2 results

Test 1		
Att E2/E1	Att E3/E2	Att E4/E3
Mean	Mean	Mean
-0.1124596	-0.10591	-0.12351
Test 2		
Att E2/E1	Att E3/E2	Att E4/E3
Mean	Mean	Mean
-0.2108867	-0.17213	-0.16393

Here in test two of the titanium block readings, the averages of the attenuation readings were higher than that of test one as the tables below display. One reason for this was that the first recording of test two offset the averages, as this was taken at random positions it could have found a defect or material discontinuity, that wasn't spotted during test one. The fact that taking random position measurements gave higher attenuation losses on test two could be put down to one of two

reasons, an operator error or as different points of the sample were measured different readings were found.

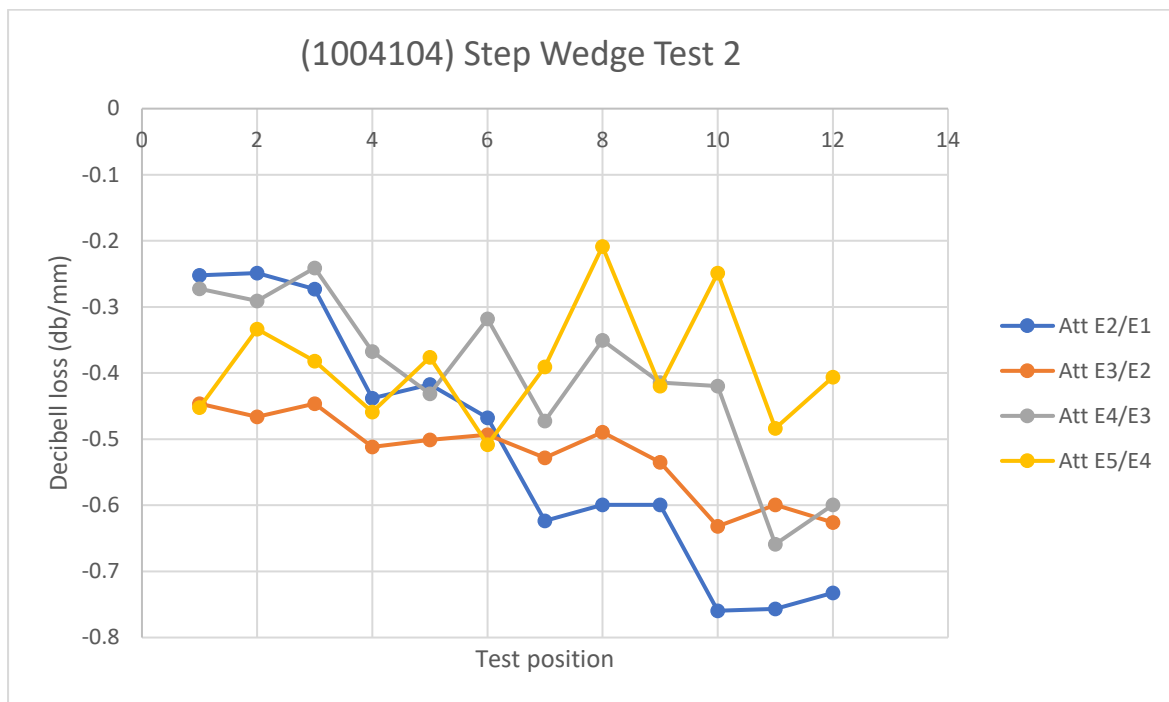


Figure 14 Step wedge test 2 results

During the second step wedge test, three recordings per step were taken. The difference here to the first test is that the velocity is set at, meaning the wavelength and near field will need recalculating.

Dimater of crystal (1004431) = 9.5mm

$$\lambda = \frac{6050}{5 * 10^6} = 1.21 * 10^{-3} \text{Metres}$$

$$\text{Near field} = \frac{D^2}{4\lambda}$$

$$\frac{((9 * 10^{-3})^2)}{(4 * (1.21 * 10^{-3}))} = 0.0167 \text{Meters}$$

Therefore, we have a near field distance of 16.7mm. This means we would expect that as we got into the top step (20mm) we would start to see more correlation between the results. As we can see from the graph this is not the case, on the contrary as we get towards the top step there appears to be less correlation at the point when we would expect to be out of the near field.

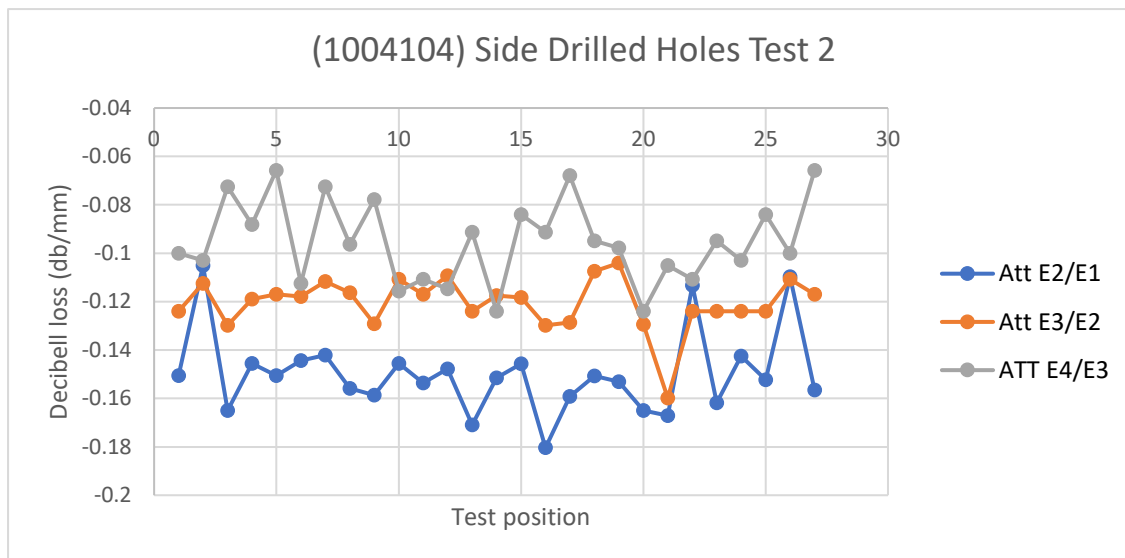


Figure 15 Side drilled holes block test 2 results

Test 2		
E2/E1	E3/E2	E4/E3
STD DEV	STD DEV	STD DEV
0.017	0.011	0.017
Test 1		
E2/E1	E3/E2	E4/E3
STD DEV	STD DEV	STD DEV
0.043	0.084	0.062

As predicted here in the second test we can see closer correlation between the readings, also there is less deviation since data was no recorded over the side drilled holes. If we look at the tables above representing the standard deviations over the calculated attenuations, we can see that in test one the data varies from the mean than the recorded data in test two. Ghost echoes were a problem recognised in this test of steel block, here sound waves travelling down would meet sound waves returning to the probe which caused an additional unexpected echo, this happened more so in the steel block as there was less attenuation so the sound wave had more energy returning to the probe quicker. This was spotted in test one but assumed to be problems from the side drilled hole, here now we can determine it was a ghost echo.

This recording of attenuation will be more valid than the first test as the readings show less standard deviation, and the side-drilled holes were avoided which caused absorption and scattering of the soundwave.

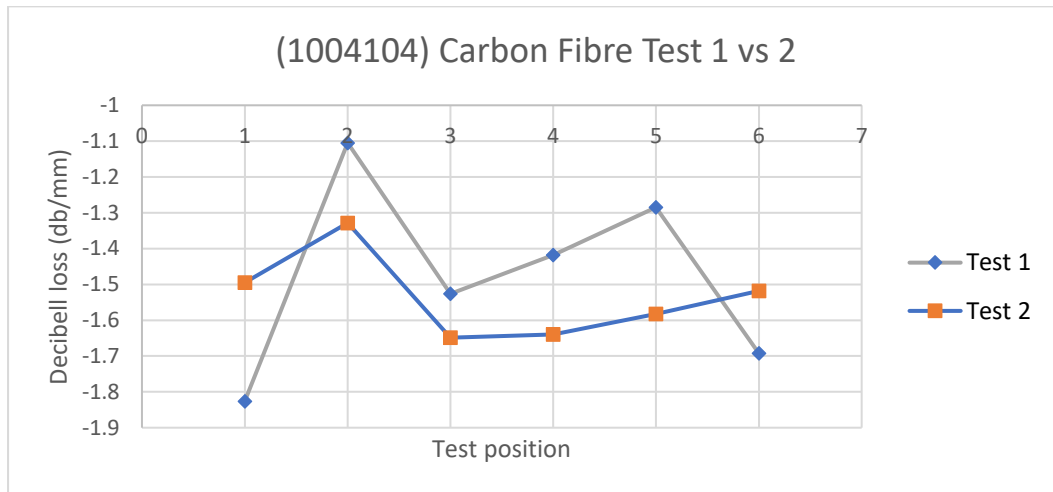


Figure 16 Carbon fiber test 2 results i)

We were only able to get one reading of attenuation from the carbon fibre, this meant that both readings could be plotted together without visibly displaying too much data, which be the case if the metals were plotted together for all attenuation readings. The readings for both tests here were taken at positions where a clear first back wall could be recorded, these positions were avoiding weaves crossing over, which was where sound was being absorbed and reflected.

The graph below shows the average attenuation in tests one and two, we can see that although some points have a wide deviation from one to another, the average reading of attenuation lies between 1.45 and 1.55.

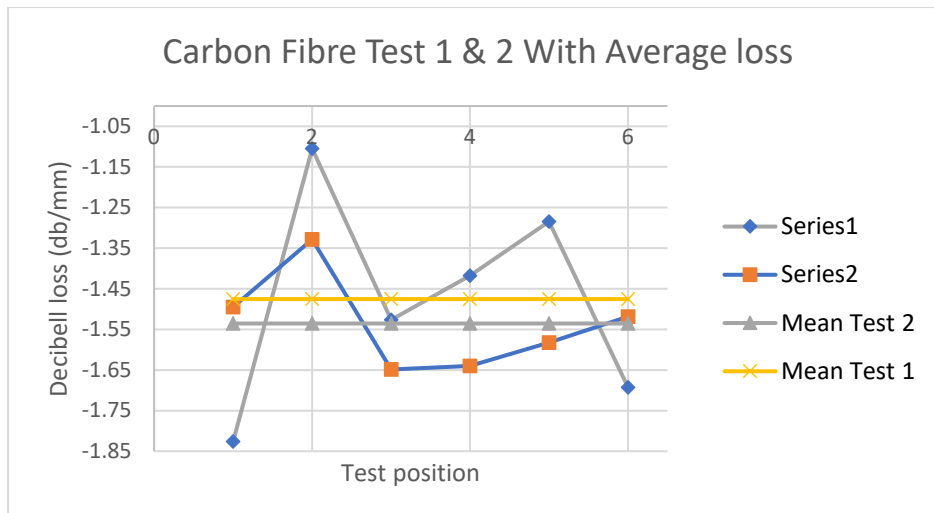


Figure 17 Carbon fibre test two results ii)

6.3 Machine Calibration & Human Error

The second test where readings were taken at random locations was repeated in test three, but this time we would use different ultrasonic equipment, with a different probe and different UT unit. In the following set of graphs, we can the mean values between test two and test three are compared, this is from taking sampling at random positions for both tests but with different equipment (test three results can be found in appendix 5).

The idea behind changing equipment was that we may be able to differentiate between a possible machine calibration issue, human error, or encountering a defect in taking the readings. If we are to see close correlation between the average attenuation readings, we will know that the two sets of equipment are closely calibrated and our results are trustworthy and any other unexpected reading could be put down to human error or a defect. The graphs displayed are the mild steel (side drilled

holes), carbon fibre and titanium (step wedge comparison appendix 6).

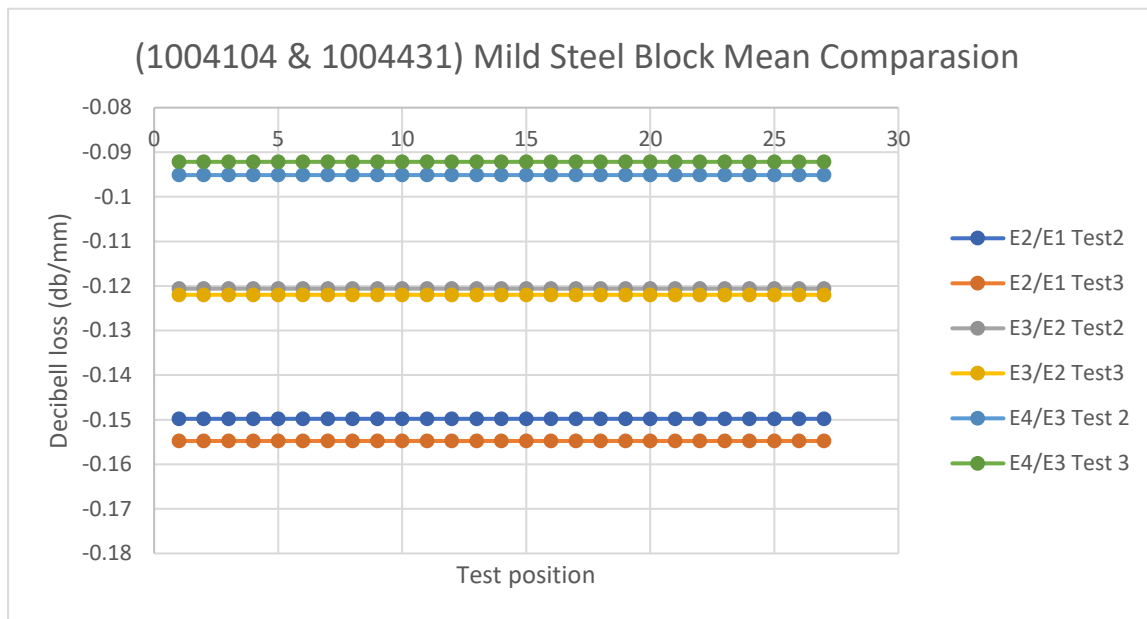


Figure 18 Steel block machine calibration

In the graph above we can see the average attenuation readings taken from the two different sets of equipment displaying closely correlated data within the mild steel. This graph indicates that the machines are calibrated closely to one another and giving true readings to within.

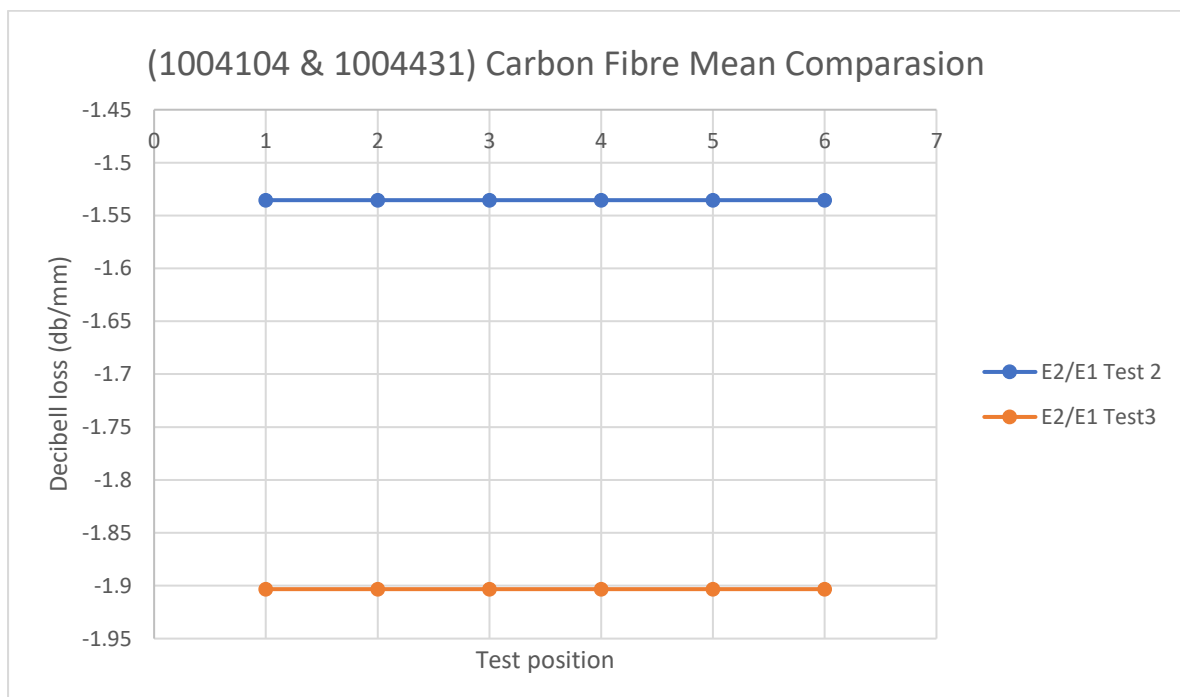


Figure 19 Carbon fibre machine calibration

The comparison of test two and three carbon fibre readings above shows wider variation than the mild steel block. Here we have a difference of, as we have seen machine calibration to be reasonable in the mild steel block we can make the judgement that the difference in average attenuation between test two and three is down to the material being non-homogeneous. Part of this variation could be put down to operator error in not using enough couplant or not positioning the probe correctly, but through all three tests there was wide deviation in the carbon of attenuation with so much of the sound being scattered and absorbed through different weaves of the composite.

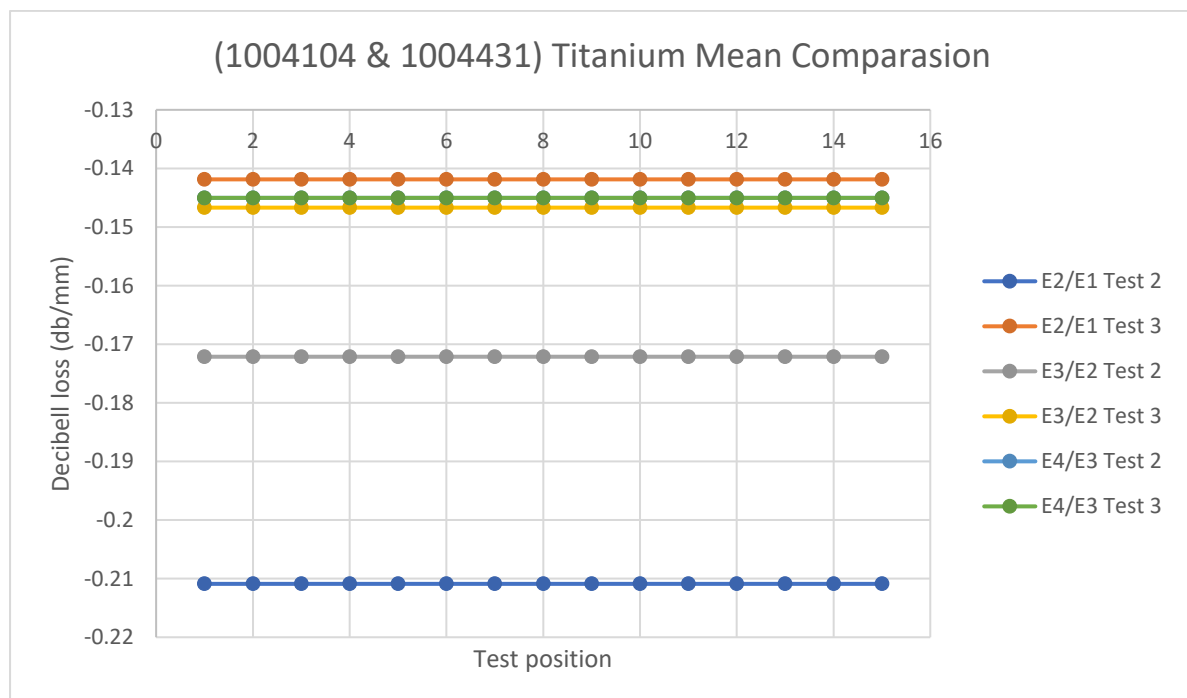


Figure 20 Titanium machine calibration

It would be expected with the titanium that we would see similar correlation as to what we did in the mild steel block as they are two metallic samples. Instead as displayed we have wide variation, especially between of test two and three. There is a variation of between these average readings of the same tests being run on the same material but with different equipment. Although this is wide variation it could be put down to human error rather than a difference in calibration between the two testing rigs. The reason being is because the close correlation in the mild steel calibration

satisfied any question of calibration, and for testing with a new operator there is a room for error with not using the correct amount of couplant, not placing the probe correctly to sample (which can be an art rather than a science).

7. Error Estimates & Discussion

The mystery material was found to have values very close to titanium when test results were checked against datasheets. Also through visual inspection, and a basic hardness comparison it was agreed upon that the most likely material of the sample would be titanium. The greatest losses were found to be in the composite material, with more correlation being found in the metallic samples, unless Near-Field testing was occurring.

The discrepancies in relating table data to measured values were put down to different alloying elements being used in the sample piece as to the specific grade of titanium displayed in the table, the visual inspection and hardness comparison gave the best argument for titanium. The closer correlation in the metallic samples found compared to the composite were due to 2 main reasons; one that the metallic samples have a homogenous packing of atoms so the sound wave has a clear path to vibrate through (unless there is a defect) whereas the composite has weaves and various layers to interrupt a sound wave, the second reason being as the sound wave hits these layers in the composite it causes reflections and scattering of the beam which then leads to the operator having to make a judgement of what is a defect and what is a sensible back wall echo to record which will inevitably lead to bad results.

There were unexpected results in the step wedge during the first three steps of test one, and the majority of test two. We expected to see correlation between readings as for one we knew there wasn't a defect in the part as it was used as a calibration tool, and that it had the metal homogeneous packing of atoms would give predictable sound vibration travel. These results were explained after it was calculated that before the final step (20mm) we were testing within the Near-Field, meaning results in this region could not be trusted.

We know that attenuation is a more general term for a series of events taking place such as scattering, absorption and reflection. If we look more closely into this we can categorise the carbon fibre attenuation as not just simply absorption and scattering of the sound wave but as a combination effects of various factors, such as material anisotropy and viscoelastic property, internal microstructure and defects, and interface condition between composite weaves (authorRan LiHong Xia, 2017).

In section 6.3 some machine calibration was carried out to try to determine whether unexpected readings were a case of either the equipment being out of calibration, a human error or a defect spotted. It was agreed upon that there were no calibration issues with the equipment after the mild steel block gave two very close averages between the two sets of equipment, therefore some odd results were likely a result of human error through not using the right amount of couplant or not applying the probe correctly.

Although frequency of the probe wasn't changed in the report wavelength (3.5) has a large bearing on attenuation. Smaller wave lengths will attenuate easier as they will get caught up in the grain structure of the material and lose energy, whereas larger wavelengths will skip over the grain structures so will attenuate less. Although with too big a wave length you would miss a defect, when

inspecting so we typically aim for a wavelength of twice the size of a defect, as a minimum wavelength. Higher frequencies attenuate more because they create smaller wavelengths, Mažeika, and Vladišauskas (L. Mažeika, 2010) describe in their conclusion on a paper about longitudinal wave attenuation “The signals with the frequencies higher than 4MHz are attenuated strongly, and their central frequency is reduced significantly even after several centimetres propagation in plastic material”. This suggests that if we would have changed the wavelength we would have seen a difference in the amount of sound attenuated.

8. Conclusion

It can be seen from the tests carried out and the data recorded that differences exist between attenuation in metallic samples in comparison to composite samples. These differences can be seen in the amount of sound lost through the composite material in the graphs of section 6, where the composite was losing roughly in comparison to a mild steel block losing.

As the weave pattern, fibre size and grade of epoxy was unknown within the carbon fibre sample we could not categorise this sound loss being due to a weave direction reflecting the sound in a specific orientation, just that a significant amount of sound was being attenuated within the weaves.

Through research and testing it was decided that the results found were because of the structured packing of metallic atoms and their ability to transport sound waves, as oppose to the composites non-homogenous properties. Unexpected results were narrowed down to three situations, in the case of the step wedge it was calculated that we were testing within the near field for most of the test, there was some human error in the composite readings, and it could be assumed that there were some possible material discontinuity and defects spotted in certain testing positions.

9. Bibliography & References

- B. Raj, . T. (2007). *Practical Non-Destructive Testing*. Moriston House, 75 Springfield Rd, Chelmsford CM2 6JB: Alpha Science International Ltd; 3rd Revised edition edition .
- B. Raj, . T. (2007). Practical Non-Destructive Testing. In . T. B. Raj, *Practical Non-Destructive Testing* (pp. 93-98). Moriston House, 75 Springfield Rd, Chelmsford CM2 6JB: Alpha Science International Ltd.
- Blitz, J. (1996). *Ultrasonic Methods of Non-Destructive Testing*. Chapman and Hall : London.
- Cambridge. (2000). *Attenuation*. Retrieved from www.phase-trans.msm.cam.ac.uk:
<https://www.phase-trans.msm.cam.ac.uk/2000/amjad/b.pdf>
- PRETOR-PINEY, G. (2010). THE WAVEWATCHERS COMPANION. In G. PRETOR-PINEY, *THE WAVEWATCHERS COMPANION* (p. 83). London: Bloomsbury.
- www.azom.com. (2017, November 01). *www.azom.com*. Retrieved from www.azom.com:
<https://www.azom.com/article.aspx?articleid=1341>
- www.nde-ed.org. (01, October 2017). *Ultrasonics*. Retrieved from www.nde-ed.org:
<https://www.nde-ed.org/EducationResources/CommunityCollege/Ultrasonics/EquipmentTrans/characteristicspt.htm>.
- www.nde-ed.org. (2017, October 01). *Ultrasonics*. Retrieved from www.nde-ed.org:
<https://www.nde-ed.org/EducationResources/CommunityCollege/Ultrasonics/Introduction/description.htm>
- www.nde-ed.org. (2017, October 1). *Wave propagation*. Retrieved from www.nde-ed.org:
<https://www.nde-ed.org/EducationResources/CommunityCollege/Ultrasonics/Physics/wavepropagation.htm>
- www.qualitydigest.com. (2017, October 10). *www.qualitydigest.com*. Retrieved from www.qualitydigest.com:
[https://www.qualitydigest.com/nov03/Images/Articles/Ultrasonic\(NearFar_Field\).jpg](https://www.qualitydigest.com/nov03/Images/Articles/Ultrasonic(NearFar_Field).jpg)
- www.rfcafe.com. (2017, November 01). *www.rfcafe.com*. Retrieved from www.rfcafe.com:
<http://www.rfcafe.com/references/general/velocity-sound-media.htm>.

www.sengpielaudio.com. (2017, October 21). *www.sengpielaudio.com*. Retrieved from
www.sengpielaudio.com: <http://www.sengpielaudio.com/FilterBandwidth09B.gif>

authorRan LiHong Xia, Q.-Q. (2017). *A New Approach for Quantitative Evaluation of Ultrasonic Wave Attenuation in Composites*. Netherlands : Springer Netherlands.

L. Mažeika, R. Š. (2010, January 01). *Measurement of velocity and attenuation for ultrasonic longitudinal waves in the polyethylene samples*. Retrieved from
citeseerx.ist.psu.edu:<http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.697.6488&rep=rep1&type=pdf>

10. Appendix

1. Steel ball bearing hardness test

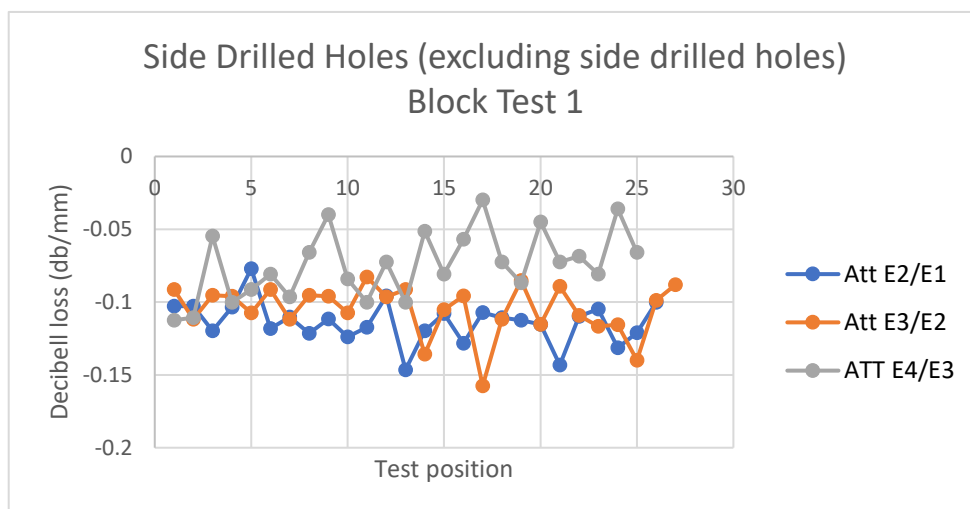


2. Scales validation

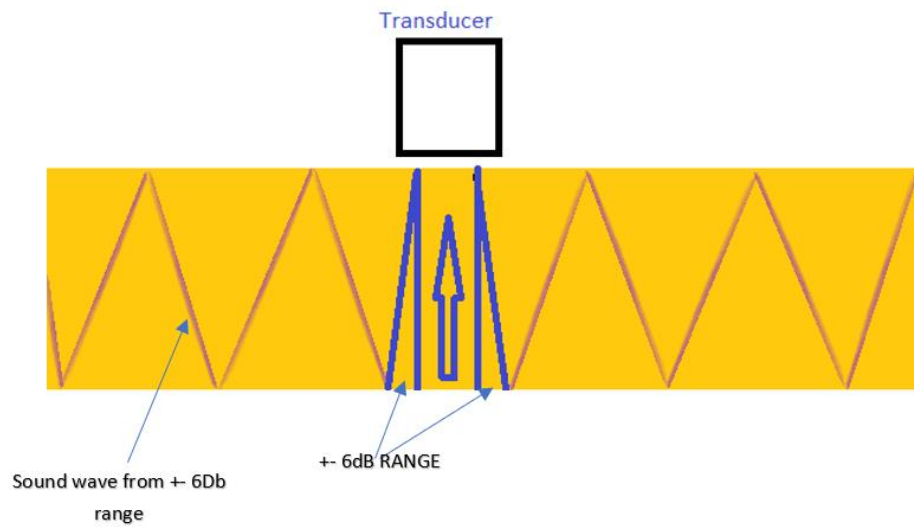


The 100 gram calibration piece measured in at 100.01 grams

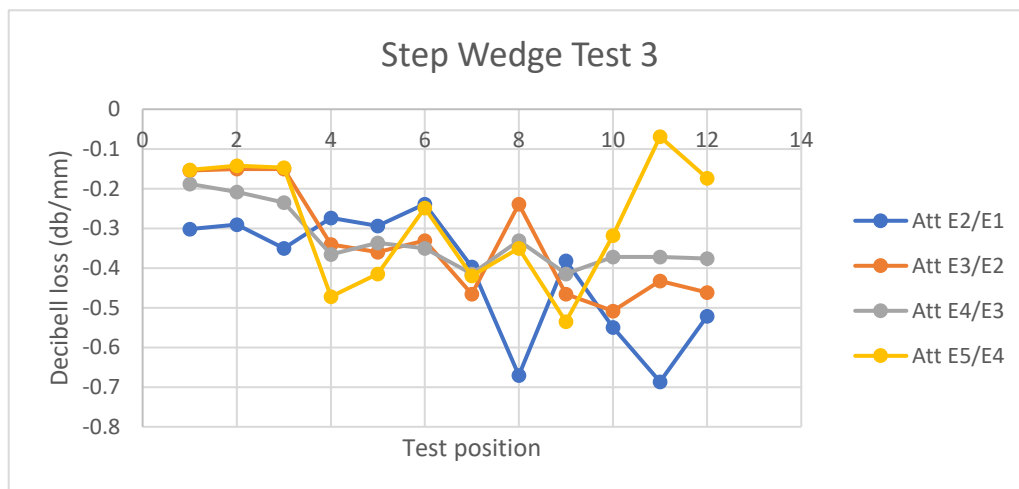
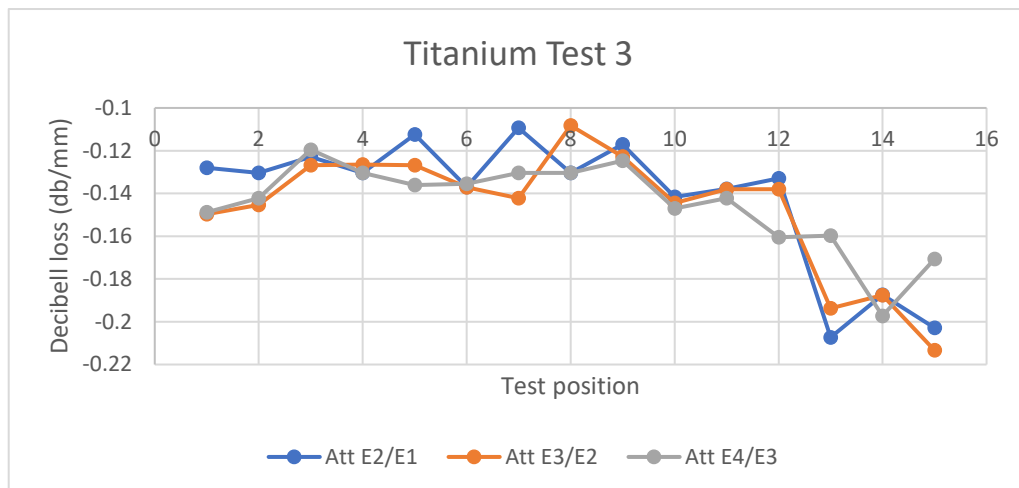
3.

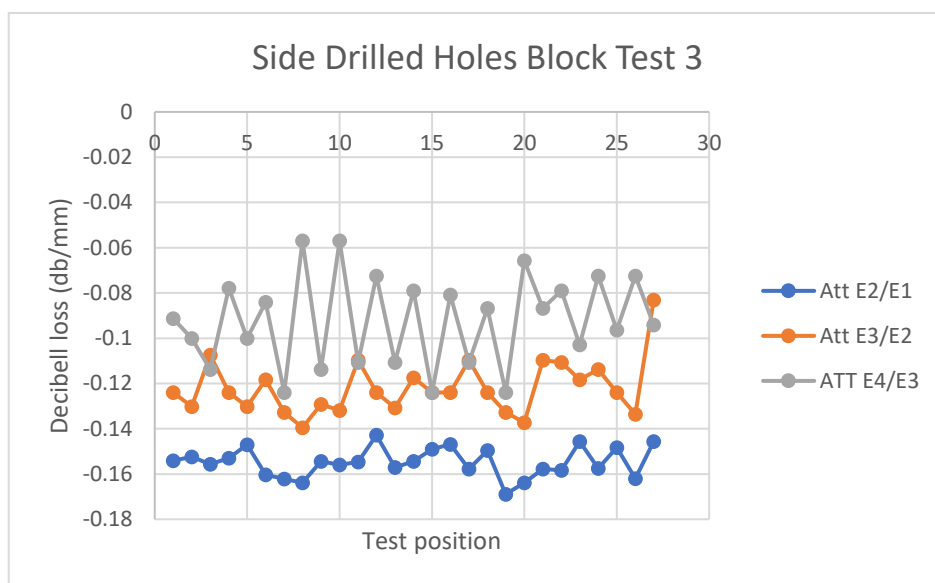
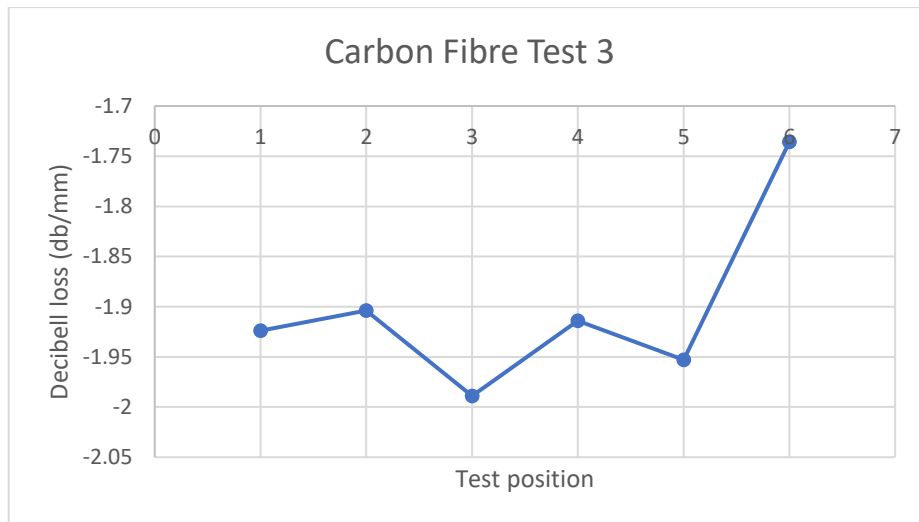


4.



5.





6. Step wedge machine calibration comparison

