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Through Wall Sizing Accuracy Analysis

Date: 13/12/24

Title: Comparing operator accuracy when using a new ultrasonic thickness gauging procedure to determine system effectiveness.

Abstract:

This paper uses statistical analysis to assess the performance of a new ultrasonic thickness gauging procedure with different operators. When comparing the operators, number 4 proves to be most accurate and reliable with consistent results which deviate less than $\pm 0.5\text{mm}$ from the results trendline. When analysing other operator results, inconsistencies and lack of detection cause the method to be dependent on operator skill and equipment calibration.

Introduction and Apparatus

This experiment is part of a larger probability of detection study to assess performance of a new ultrasonic thickness gauging procedure. There are 10 operators testing over 21 different defect sizes given at 2 decimal places (figure 1). This lab report uses linear regression and statistical analysis to determine sizing accuracy of each operator, and effectiveness of new thickness gauging procedure.

Defect	true size	Op1	Op2	Op3	Op4	Op5	Op6	Op7	Op8	Op9	Op10
A	0.25	1.00	0.00	0.50	0.50	0.50	0.00	1.00	0.30	0.50	0.80
B	0.27	1.00	0.00	1.00	0.73	1.20	0.50	1.00	1.20	0.50	0.80
C	0.28	1.00	0.00	0.50	0.76	1.00	1.20	1.00	0.70	0.50	1.30
D	0.40	1.20	1.00	1.00	0.91	0.50	1.00	1.00	0.80	0.60	1.50
E	0.40	1.40	1.00	1.10	0.98	1.20	1.00	1.00	0.90	0.20	1.60
F	0.50	1.10	1.00	0.80	0.79	0.90	1.00	1.20	0.50	0.00	1.00
G	0.52	0.90	1.50	1.00	1.01	1.50	1.10	1.00	0.70	1.00	0.90
H	0.55	0.50	0.90	1.20	0.96	1.20	0.80	1.00	0.40	1.30	1.60
I	0.70	2.00	1.60	1.20	1.35	1.50	0.90	1.00	1.00	1.60	2.20
J	0.98	1.90	2.00	1.60	1.31	1.00	0.80	1.00	1.40	0.50	1.80
K	1.12	1.00	1.80	1.80	1.37	0.50	1.00	1.50	1.30	1.80	2.00
L	1.15	2.20	1.00	1.50	1.56	1.80	1.30	1.50	1.20	1.80	2.00
M	1.10	2.00	1.60	1.50	1.60	2.00	1.40	2.00	1.60	0.50	2.20
N	1.30	2.20	2.00	2.00	1.73	2.10	0.90	1.50	1.70	1.70	2.00
O	1.60	2.00	2.00	1.50	1.56	0.80	0.90	2.00	1.50	1.20	2.00
P	1.80	2.40	2.00	3.20	2.14	2.00	1.40	2.50	1.10	2.20	2.50
Q	2.10	3.50	2.50	3.00	2.49	1.80	2.30	2.00	2.60	2.00	3.20
R	2.70	2.80	2.50	3.50	2.97	3.00	3.20	3.50	2.20	2.50	3.50
S	4.90	5.70	4.50	4.40	4.87	4.50	4.50	5.50	5.50	4.20	5.40
T	6.00	7.00	6.50	5.50	6.17	5.50	6.20	6.50	6.00	5.30	6.70
U	7.50	8.00	7.20	6.50	6.99	6.00	6.25	8.00	6.50	6.50	6.90

Figure 1: Ultrasonic Thickness Gauging Data.

Analysis Methodology

Probability of Detection – Hit/Miss Method

To determine probability of detection (POD) a hit/miss technique with four assessment probabilities can be applied to each operator and flaw. This technique uses parameters in table 1 to compare against (Damira, et al., 2021). For this document, binary logistic regression model is used where in effect: true positive is represented as 1 (detected), and false negative, false positive and true negative are represented by 0 (not detected).

Table 1: Hit/Miss Probability of Detection

Defect	Detected	Not Detected
Existing	True Positive (TP) The defect exists and is detected.	False Negative (FN) The defect exists but is not detected.
Non-Existing	False Positive (FP) A defect is detected but does not exist.	True Negative (TN) Defect not present and not detected.

Probability of Sizing

By completing a destructive test (DT) alongside an NDT, a scatter plot can be used to compare the two and analyse confidence bounds, accuracy and error range. A probability of sizing (POS) study can be used to analyse reliability, repeatability and accuracy of an experiments methodology and results (Wallace & Fahr, 2014).

Calculations and Error Estimates

Probability of Detection – Logistic Regression

The formula for logistic regression is shown in equation 1 where POD is probability of detection, x is flaw size data and beta are coefficients based on log odd x variables (Terzioğlu, 2022). This equation can be applied to each operator binary hit or miss results for each defect (equation 2).

$$POD = \frac{1}{1+e^{-(\beta_0+x*\beta)}} \quad (1)$$

$$\frac{1}{1+e^{-(-112.0468+(0.25 \times 330.1306))}} = 1.52 \times 10^{-13} \quad (2)$$

Error Mean

The error mean ($\bar{x}$) is calculated to determine average error (x) result for each operator over ‘n’ sample size. This can be used to compare against others and assists in determining most accurate operator. Two types of errors can be calculated, mean error (equation 3) or absolute mean error (equation 5). The absolute mean error accounts for underestimations of true defect instead of ‘reducing’ error. Equations 4 and 6 show the difference in error results when using equations 3 and 5 respectively.

$$\bar{x} = \frac{\sum x}{n} \quad (3)$$

$$\bar{x} = \frac{14.68 \text{ mm}}{21} = 0.699 \text{ mm} \quad (4)$$

$$|\bar{x}| = \frac{\sum |x|}{n} \quad (5)$$

$$|\bar{x}| = \frac{15.02 \text{ mm}}{21} = 0.715 \text{ mm} \quad (6)$$

Probability of Sizing

To add tolerance limits, a line of best fit can be added to a scatter plot of test data results. From this line of best fit an equation of the linear line can be retrieved in the form of equation 7. To add tolerance limits (equation 8) of ± 0.5 as an example, this value is added/subtracted to y-intercept (equation 9).

$$y = mx + c \quad (7)$$

$$y = mx + (c \pm tol) \quad (8)$$

$$y = 0.8727x + 0.9704 \pm 0.5 \quad (9)$$

Standard Deviation - Population

The standard deviation (σ) is used to determine variation in data from a set of results. This document uses the population version, shown in equation 10 (Rumsey, 2016). In this equation, x_i represents individual population value, $\bar{x}$ population mean and 'n' population size. Equation 11 is an example calculation of standard deviation for operator 1.

$$\sigma = \sqrt{\frac{\sum(x_i - \bar{x})^2}{n}} \quad (10)$$

$$\sigma = \sqrt{\frac{3.3098}{21}} = 0.397 \quad (11)$$

From the standard deviation, 95% confidence limits can be applied to operator POS graphs (equation 13). The upper and lower limits are applied to each data set by adding or subtracting Z multiplied by standard deviation (equation 12) where Z = 1.96 for 95% confidence limit (Asare, et al., 2018).

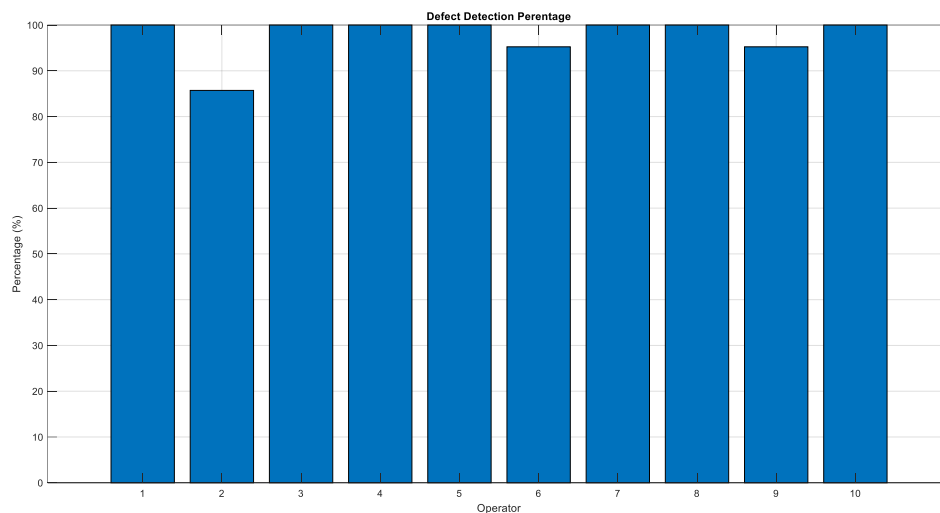
$$y_{Confidence\ limit\ (95\%)} = mx + c \pm (\sigma X Z) \quad (12)$$

$$y_{Upper\ limit\ (95\%)} = 1.0021x + 0.6954 \pm (0.397 X 1.96) \quad (13)$$

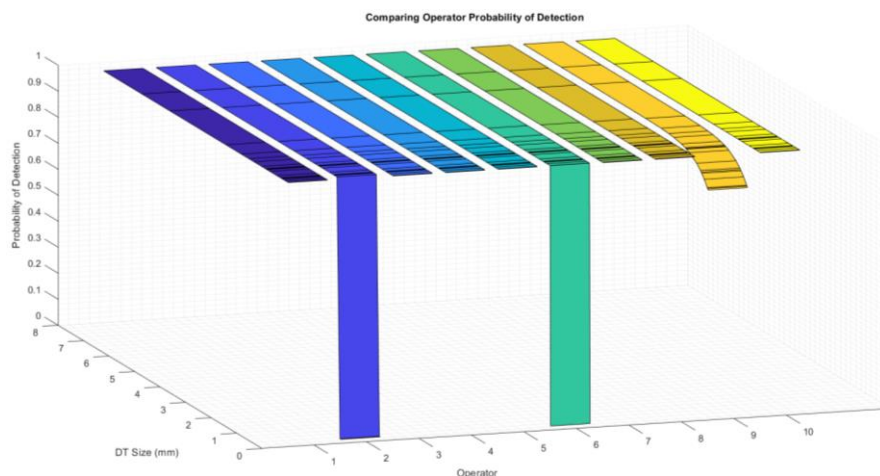
Results and Discussion:

Hit or Miss Probability of Detection

Using binary hit/miss logic, bar chart in graph 1 compares error detection percentage for each operator. Interpretations of these results are 30% of operators missed at least one defect with operator 2 missing a total of 3. Operators 6 and 9 both missed 1 defect each. All other operators have a 100% POD rate for defects within a range of 0.25-7.5 mm. Reasoning behind lack of defect detection is due to a lower frequency used or incorrect use of equipment. To improve probability of defect detection, the correct frequency should be determined by accuracy needed. Increasing frequency will decrease wavelength and increase chances of detecting smaller defects (Zhang, et al., 2023). From graph 2, 70% of operators are at 100% probability of detection, this is due to the defects not being small enough for most operators to miss. However, once defects are smaller than detection threshold/equipment capabilities all operators will reach a 0% POD.



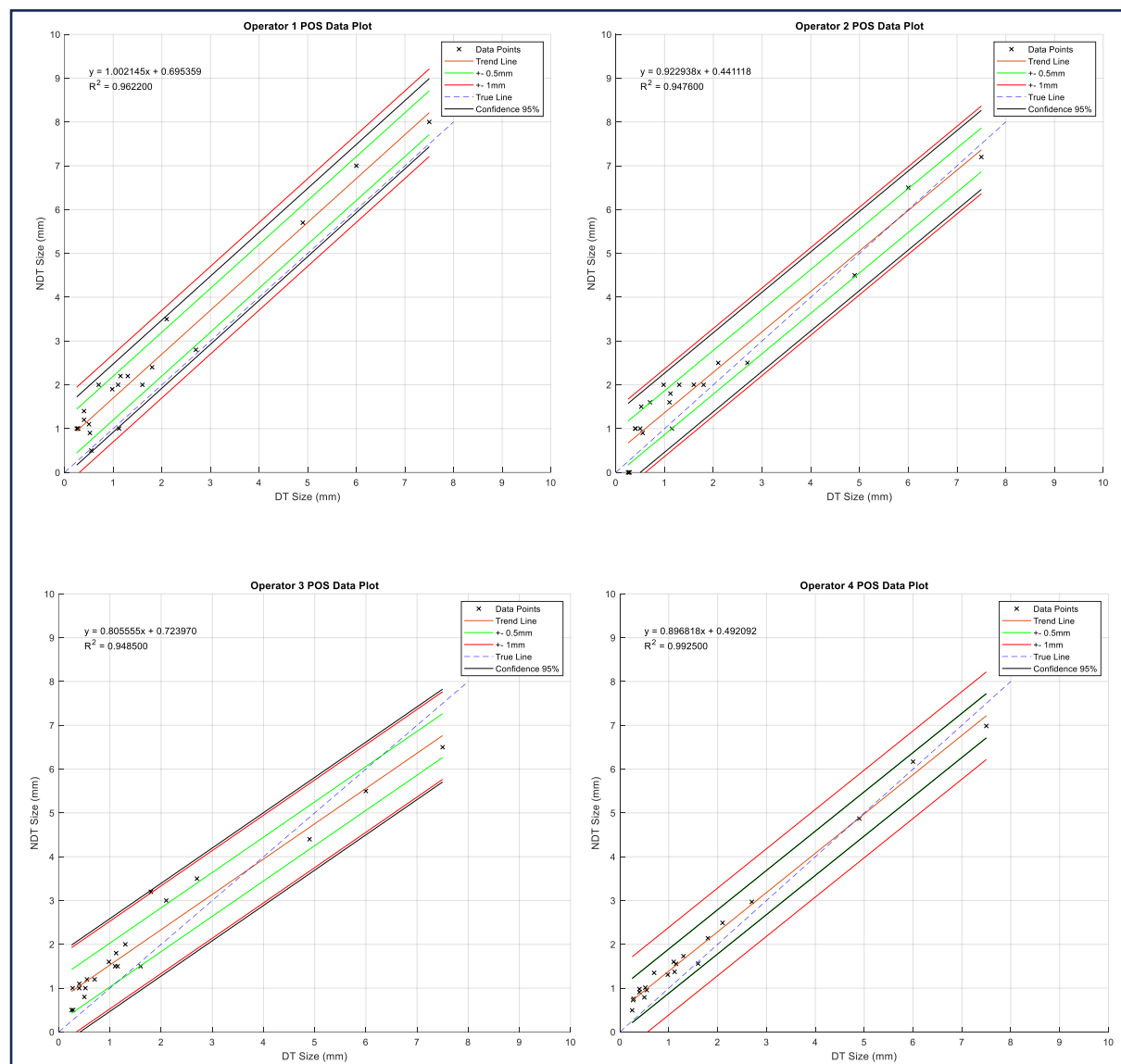
Graph 1: Operator Defect Detection Percentage.



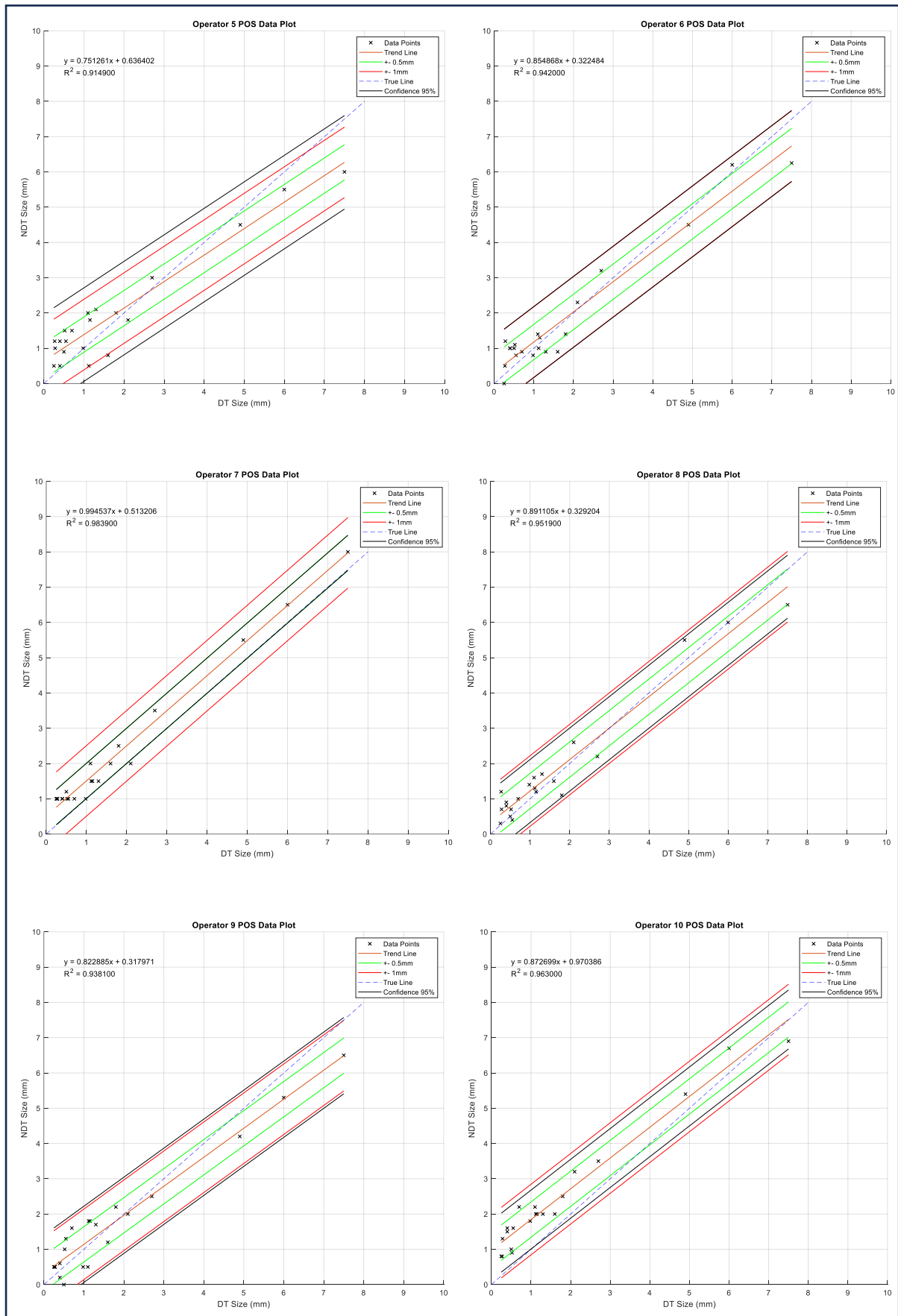
Graph 2: Logarithmic Regression Plotting of POD.

Probability of Sizing

Subplots in graphs 3 and 4 show probability of sizing graphs for each operator, where true destructive testing results are compared against operator non-destructive results. On each graph the following is included: equation of trendline, R^2 value, dotted true line, ± 0.5 and 1mm tolerance limits, data points for that operator and a 95% confidence limit. From these graphs, operator 4 has the most consistent results by not exceeding $\pm 0.5\text{mm}$ off the trendline. Operator 5 has least consistent results where variations from trendline in some cases exceed $\pm 1\text{mm}$. Additionally, operators 1 and 5 have trendlines furthest away from true line which can be interpreted with the gradient and y-intercept varying the greatest from true line's 1 and 0 respectively.



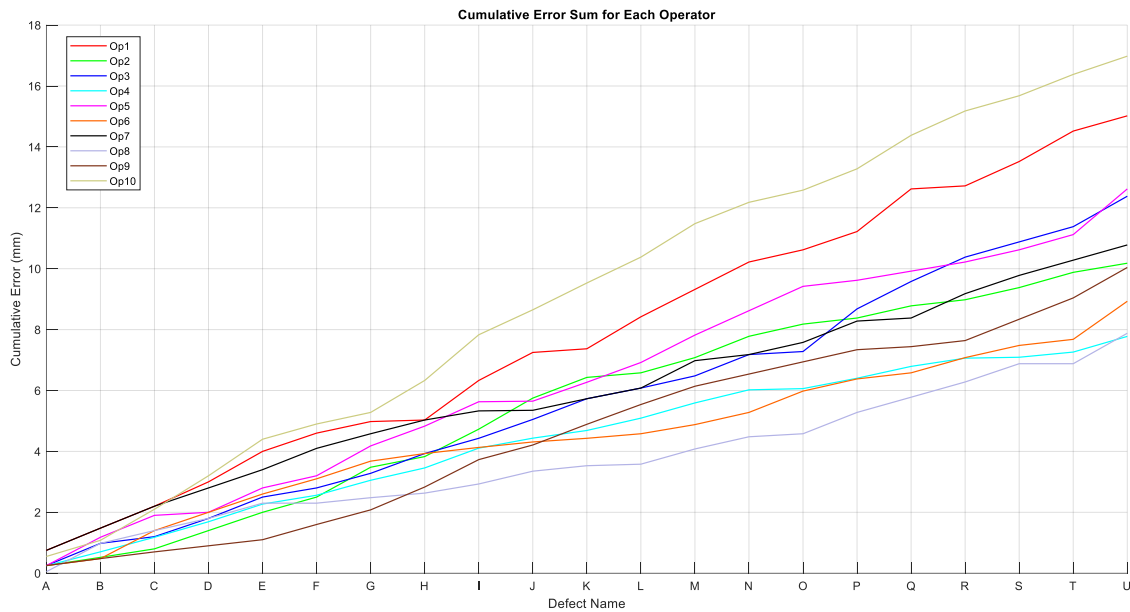
Graph 3: Probability of Sizing Subplot for Operators 1-4.



Graph 4: Probability of Sizing Subplot for Operators 5-10.

Operator Errors

An initial comparison of errors is shown in graph 5 with a plot comparing operators' size of cumulative error over each defect. The most noticeable points to make are that operator 4 has the smallest total error, with operator 8 slightly higher but showing more consistency. On the contrary, operator 10 has highest error across most defect sizes. Worth noting is that operator 9 is more accurate than all others at smaller defect sizing but this changes once defects exceed size 0.55mm (H).



Graph 5: Comparing Operators Cumulative Error.

Graph Data Values

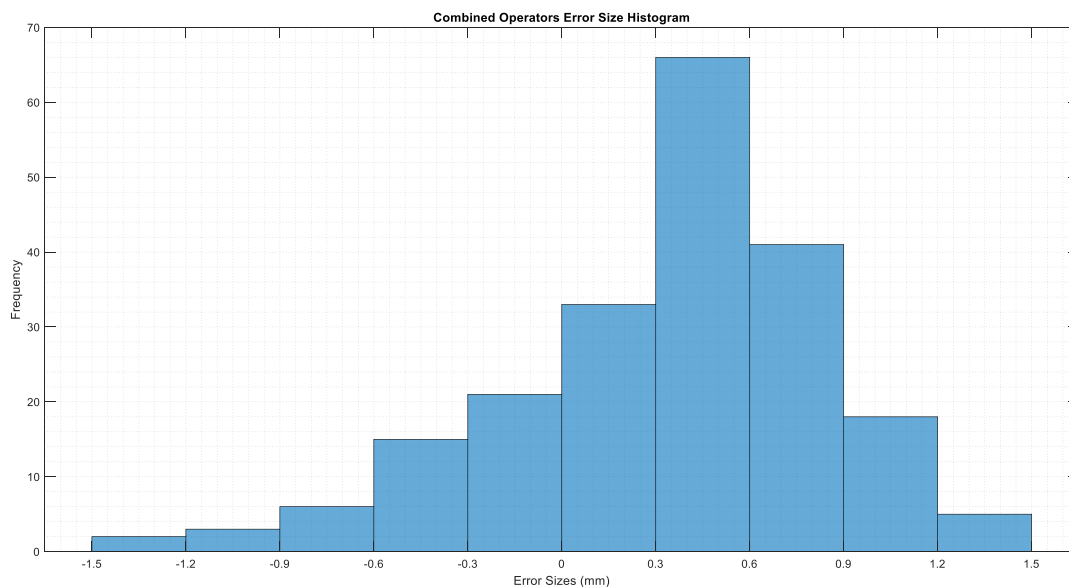
Using graphs and tables in all above sections table 2 uses conditional formatting to compare all calculated values where green is best and red is worse. From this table, the data interprets operator 4 is most accurate and closely followed by operator 8. The coefficient of determination (R2) “measures the quality of fit of the regression equation to measured variables” (Dodge, 2008) where a value closest to 1 (100%) equates to a perfect fit. From table 2, the highest R2 value of 0.9925 returns operator 4 which also has lowest absolute mean error value and second lowest standard deviation. By interpreting this data, operator 4 is both consistent and accurate.

Table 2: Calculated Values Comparison for Each Operator.

Calculated Values	Op1	Op2	Op3	Op4	Op5	Op6	Op7	Op8	Op9	Op10
R Squared	0.9622	0.9476	0.9485	0.9925	0.9149	0.9420	0.9839	0.9519	0.9381	0.9630
Gradient	1.0021	0.9229	0.8056	0.8968	0.7513	0.8549	0.9945	0.8911	0.8229	0.8727
Y-intercept	0.6954	0.4411	0.724	0.4921	0.6364	0.3225	0.5132	0.3292	0.318	0.9704
Mean Error	0.6990	0.3086	0.3895	0.3146	0.2086	0.0729	0.5038	0.1419	0.0133	0.7514
Absolute Mean Error	0.7152	0.4848	0.5895	0.3703	0.6010	0.4252	0.5133	0.3752	0.4781	0.8086
Standard Deviation	0.3874	0.4495	0.5273	0.2521	0.6598	0.5015	0.2482	0.4449	0.5380	0.4159

Testing Method Review

The new ultrasonic thickness gauging procedure is 70% effective at detecting flaws at a minimum size of 0.25mm, based on sample data in this document. This can be attributed to operator error but does not prove to be 100% effective at detecting defects until 0.4 mm; even then an anomaly is present where operator 9 missed defect F (0.5mm) but detected all others. Operators can make mistakes at any aspect of inspection: searching sensitivity, technique, environmental control conditions and more (Gardner, 2013). The histogram in graph 6 concludes that most measurements (66) are overestimations of true values by between 0.3-0.6mm. Aside from undetected defects by some operators, all error sizes are within ± 1.5 mm of true values. From these results it is clear the system relies heavily on the operator, significantly impacting how well equipment responds with respect to accuracy, reliability and repeatability of results (Wallace & Fahr, 2014).



Graph 6: Histogram of all Operator Errors Combined.

Conclusion:

In conclusion, the new ultrasonic thickness gauging procedure is 70% effective at detecting flaws of 0.25mm. The system accuracy and repeatability is heavily dependent on operator skills/technique, equipment setup and calibration which is demonstrated by wide variations in error and validity. From 10 different operators, number 4 was most reliable and demonstrated high levels of consistency, on the other hand, operators 1, 5 and 10 were inconsistent and varied from true results significantly. All others were relatively mediocre and similar suggesting the method is only adequate.

References (1)

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Ultrasonic Attenuation Coefficient Determination

Date: 13/12/2024

Title: Determining Ultrasonic Attenuation Coefficient of a steel block and brake disc using time-of-flight method.

Abstract:

This laboratory report calculates ultrasonic attenuation coefficient for a mild steel block and ductile cast iron brake disc using time-of-flight method. Factors that affect accuracy of these values are discussed in this report. Due to higher levels of scattering in casted components, results demonstrated the brake disc had a higher attenuation coefficient. To further verify this report further validation and error reducing methods such as velocity calibration are mentioned.

Apparatus:

- Vernier callipers
- Zero-degree 5MHz probe and leads
- Ultrasonic flaw detector
- Couplant (water and gel)
- Components: brake disc and mild steel rectangular block.

Introduction

This laboratory report details attenuation coefficient calculation of a cast iron brake disc and mild steel block using ultrasonic non-destructive testing and time of flight method (figure 2). The attenuation coefficient determines depletion rate of sound waves through a component and is crucial in ultrasonic testing where each component and material are unique.

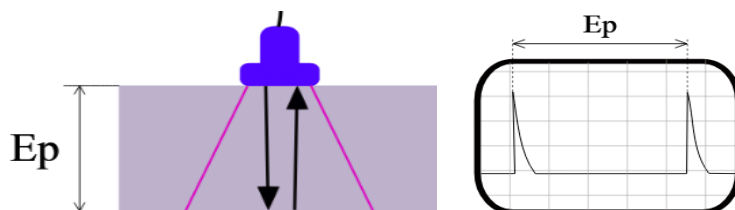


Figure 2: Time of Flight Method (Ghosh & Dwivedi, 2020).

Methodology

1. Equipment Setup: Using vernier callipers, take multiple measurements across component's (figure 3) length, width and depth. For this experiment steel block dimensions were 80mm X 19mm X 19mm ($\pm 0.25\text{mm}$) respectively and brake disc thickness, 7mm $\pm 0.25\text{mm}$. Plug in 5MHz probe and use dimensions to setup ultrasonic device range by multiplying dimensions by three (for three pulses).

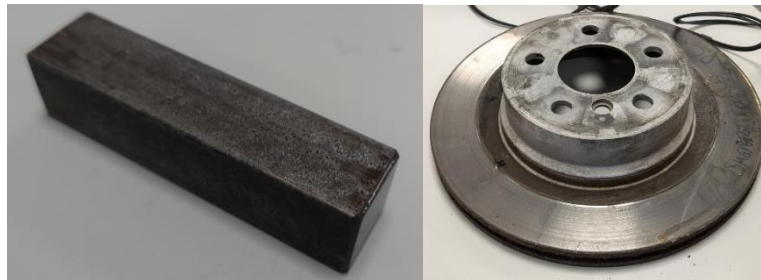


Figure 3: Mild Steel Block (Left), Brake Disc (Right)

2. Velocity Calculations: Correct velocity is needed to ensure ultrasonic distances are correct for component dimension. Utilising each materials acoustic impedance, density and dimensions a closely calculated velocity can be input into the ultrasonic device. Small adjustments to velocity may be required to reduce error. This is achieved by applying couplant and probe onto test pieces whilst comparing first echo distance at peak to measured dimensions and adjusting velocity accordingly.

3. Scanning and Gain: Once all device parameters are setup, data collection can begin. This commences with application of couplant and scanning with probe (figure 4). Samples should be taken across entirety of component surfaces due to changes in grain structure, thickness variation and surface conditions (Belvin & Burrell, 2009).

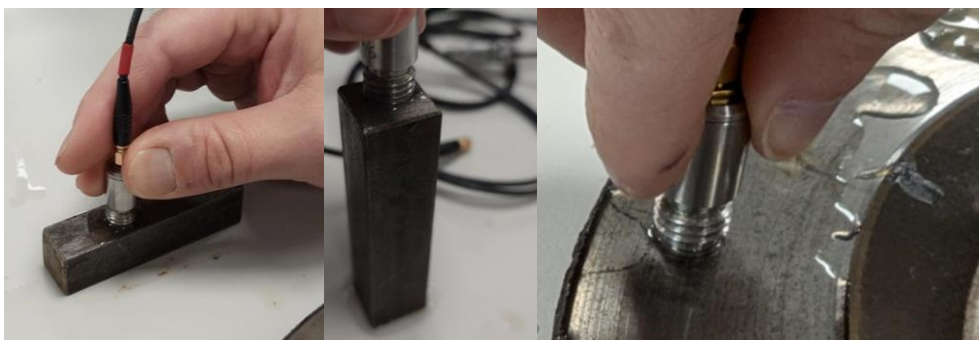


Figure 4: Scanning Components with Probe and Couplant.

4. Data Collection: Once an acceptable signal is displayed, gain parameter should be adjusted so that echo 1 reaches 70-80% of initial pulse height, this ensures echoes 2 and 3 are easily distinguished, figure 5 (Berke, 2009). Using the gate menu, values for height percentage and distance can be obtained from the ultrasonic device. Retrieve both height percentage and peak distance for first 3 echoes. Ensure multiple measurements are taken and repeat section 3 and 4 for each component/orientation.

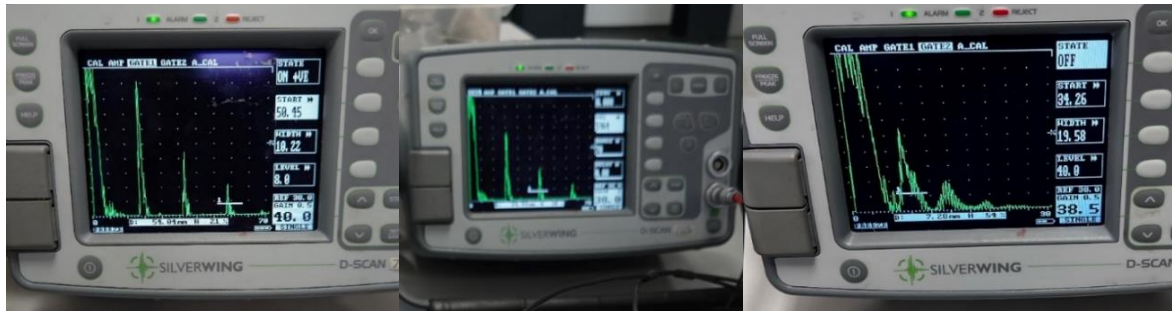


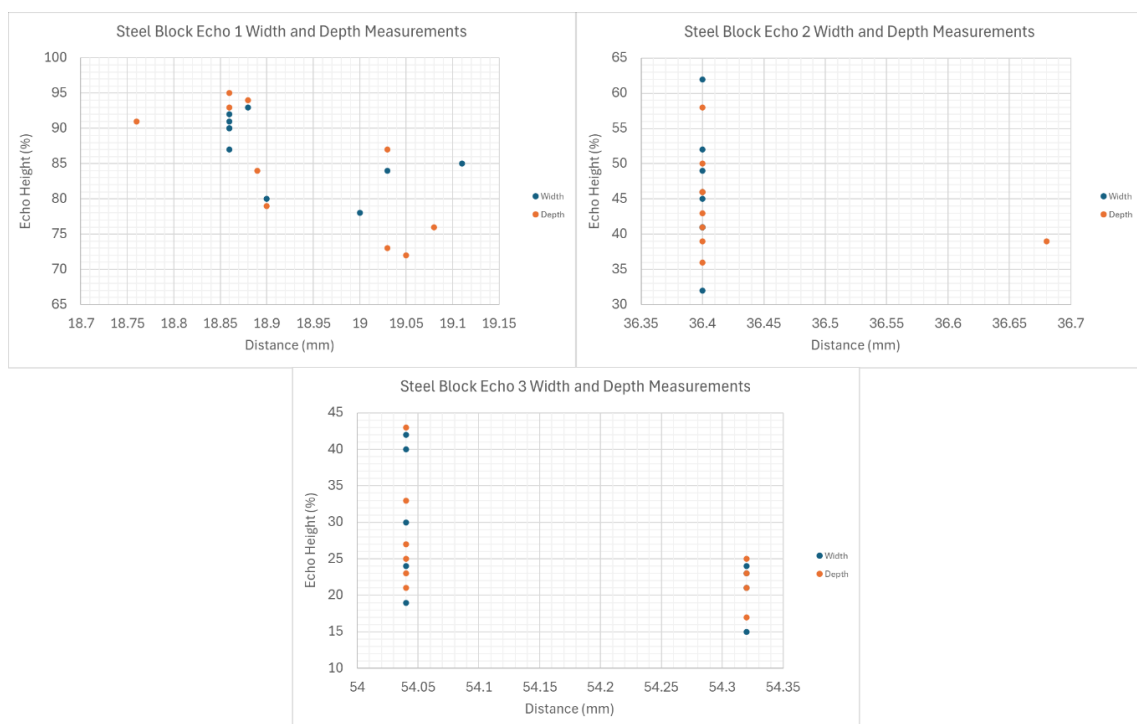
Figure 5: Echo Heights for: steel (left) 40 gain, steel (middle) 38 gain and Disc (right) 38.5 gain.

Challenges: Due to different couplant properties it was established gel presented more challenges at getting a signal reading, but once shown, tended to be clearer but jagged as gel has a higher viscosity and contains air bubbles. Water had opposite effects and was therefore selected. When selecting a couplant, industry standard practise is to ensure no damage is caused to components by corrosion or chemical break down. Once a couplant is selected, a calibration method should be applied to account for acoustic impedance of selected couplant, and no other couplant should be used after calibration (Chaplin, 2017). Although these components have good accessibility and small surface areas, a couplant delivery system could help obtain data quicker with consistent presence of couplant (Rolls Royce, 2015).

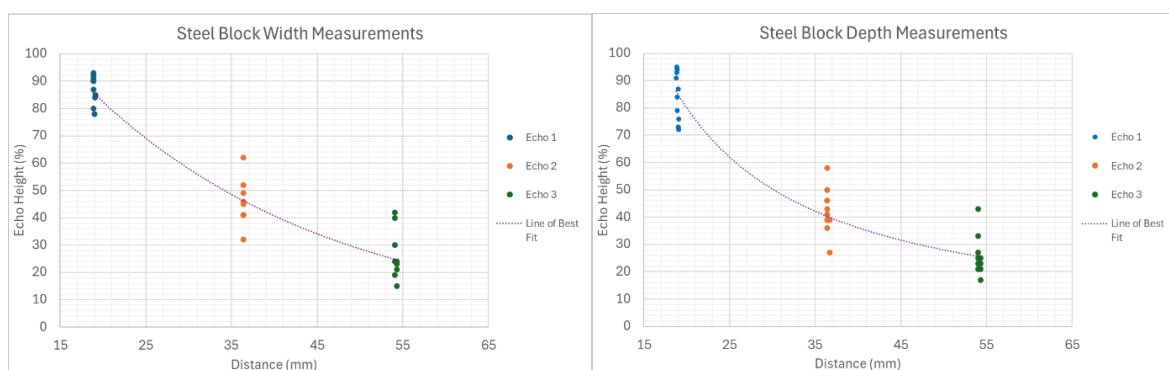
Raw Measurements and Graphs

Steel Block Width and Depth

Graph 7 ‘Echo 1-3’ shows measurements for width and depth of steel block. Plotting these results (graph 8) allows for a validation check to ensure measurements follow a trend. Larger variations in distance for depth are noticeable than width. The change in dimensions is due to variation in true thickness. Echo height variation is primarily due to gain variations and signal strength. All but 1 data points fall between an error tolerance of $\pm 0.15\text{mm}$ from true measured value (19mm). Echoes 2 and 3 data points vary unpredictably in terms of distance, increasing percentage error for each echo.



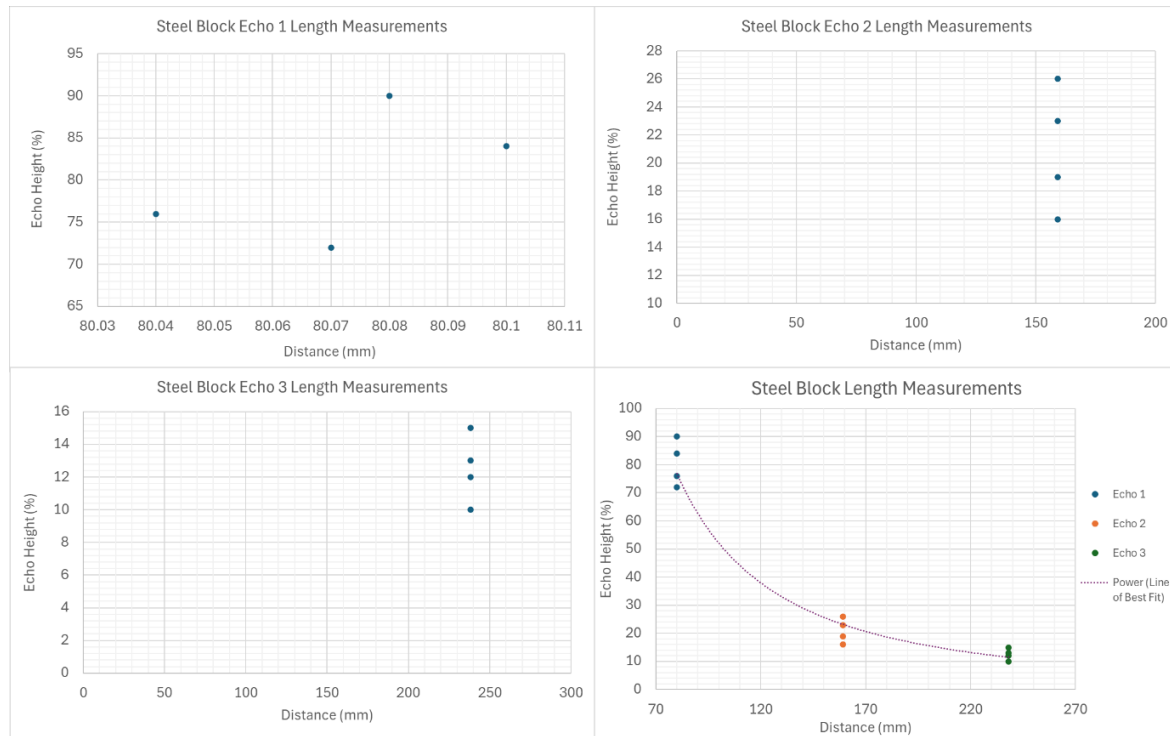
Graph 7: Steel Block Width and Depth Measurements for Each Echo.



Graph 8: Steel Block Width and Depth Plots.

Steel Block Length

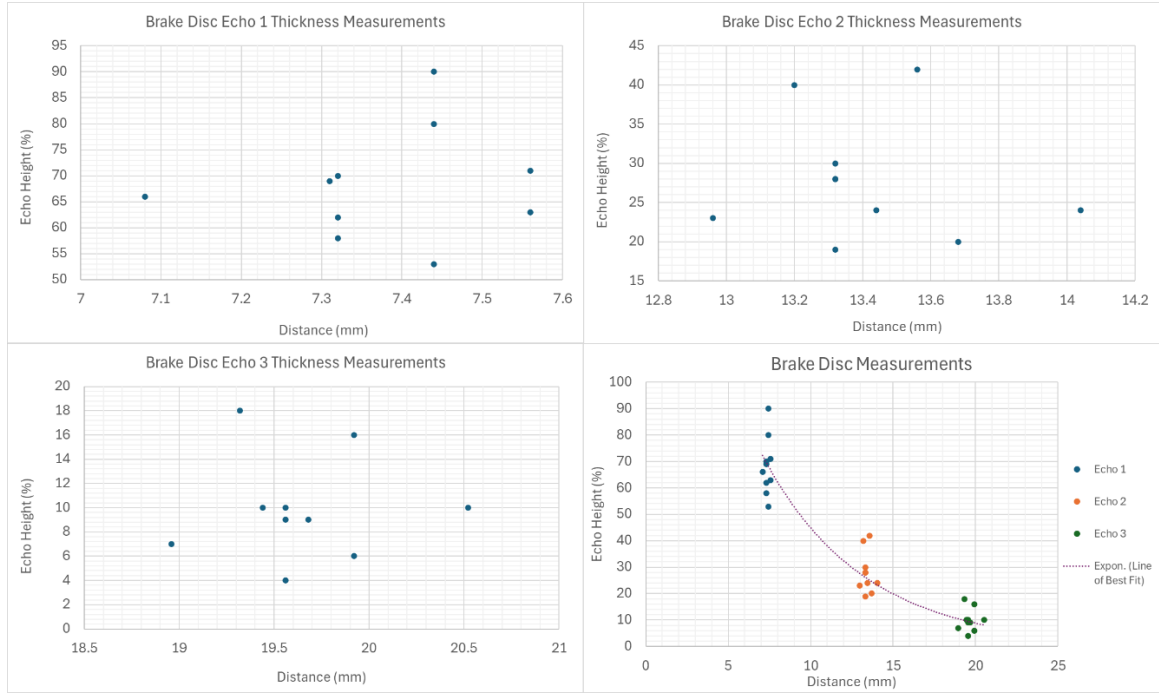
Length of block measures at approximately 80mm, as seen graph 9 ‘echo 1 length measurement’. These results are closer spread by a maximum range of 0.06mm. However, considering true dimension is 80mm, maximum error is positive 1mm. For graphs “Echo 2 and Echo 3” results show equal distances of each data point. “Steel Block Length Measurements” demonstrates an interpolation of results.



Graph 9: Steel Block Length Measurements and Plot for Each Echo.

Brake Disc Thickness

The result range for echo distance and height of brake disc was more significant than other components. This is attributed to varying thickness, surface corrosion and defects. Additionally, with lack of velocity calibration and nearfield interaction it is probable the incorrect velocity was used considering all are at least 0.08mm above measured dimension (graph 10 ‘echo 1’). This variation increases for echoes 2 and 3. The range in distance results occurs from large amounts of scattering due to surface roughness. A mathematical Gaussian height distribution model can be used to estimate deviations in surface height for Kirchhoff Approximation (figure 6) analytical scattering method (Lee, 2021).



Graph 10: Brake Disc Thickness Measurements and Echo Interpolation Plot.

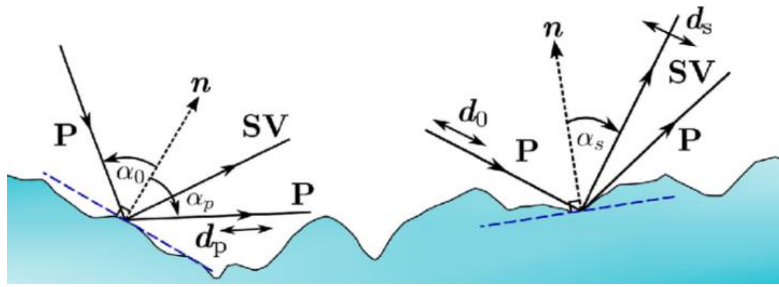


Figure 6: Kirchhoff Approximation Scattering (Allison, et al., 2022).

Calculations and Error Estimates

Wave Velocity

Estimations of initial test velocity (V) are needed to setup ultrasonic device, this is calculated using equation 1 (where: Z is acoustic impedance and ρ is density), giving equation 2. Mild steel has an acoustic impedance of approximately 46.7MRayl and density of 7850kg/m³ (Cambridge University Engineering Department, 2003).

$$V \text{ (m/s)} = \frac{Z \text{ (MRayl)}}{\rho \text{ (kg/m}^3\text{)}} \quad (1)$$

$$V = \frac{46.7 \text{ MRayl}}{7850 \text{ kg/m}^3} \approx 5949 \text{ m/s} \quad (2)$$

This approximation of ultrasound wave velocity in steel accounts for a calculated distance of 20.8mm. This 1.8mm overestimate indicates velocity is incorrect and needs refinement; as time is constant throughout, equation 3 can be manipulated (giving equation 4) to give a closer estimate to the 5444m/s velocity used, equation 5. Differences are due to variations in material thickness, errors in rounding, excluding couplant from calculations, and assumptions in materials.

$$\text{Velocity (ms}^{-1}\text{)} = \frac{\Delta \text{Distance (m)}}{\Delta \text{Time (s)}} \quad (3)$$

$$t = \frac{0.0208 \text{ (m)}}{5949 \text{ (ms}^{-1}\text{)}} \approx 3.5 \times 10^{-6} \text{ (s)} \quad (4)$$

$$V = \frac{0.019 \text{ (m)}}{(3.5 \times 10^{-6}) \text{ (s)}} \approx 5429 \text{ (ms}^{-1}\text{)} \quad (5)$$

Wavelength Calculations

From velocity (C) and frequency (f), wavelength (λ) can be calculated (equation 6) to either check for defects and/or calculate an estimate for near field distance (Martin, 2010). Equation 7 calculates wavelength for mild steel block width and depth, table 3 details other wavelengths.

$$\lambda \text{ (m)} = \frac{c \text{ (ms}^{-1}\text{)}}{f \text{ (Hz)}} \quad (6)$$

$$\lambda = \frac{5444 \text{ ms}^{-1}}{5 \text{ MHz}} = 0.0010888 \text{ m} \quad (7)$$

Near Field Distance

Calculation of nearfield (NF) distance (equation 8 and 9) will provide useful for the brake disc which has a small thickness and could be affected by wavelengths having insufficient time to fully construct. Where: crystal diameter (D) and wavelength (λ) are values obtained from table 3.

$$NF \text{ (m)} = \frac{D^2 \text{ (m}^2\text{)}}{4\lambda \text{ (m)}} \quad (8)$$

$$NF = \frac{0.010^2}{(4 \times 0.0010888)} \approx 0.02296 \text{ m} \approx 22.96 \text{ mm} \quad (9)$$

Table 3: Calculated Component Results.

Component	Dimension	Velocities			Wavelength (m)	Near Field Distance (mm)	
		Guide Velocity (m/s)	Calculated Velocity (m/s)	Experiment Velocity (m/s)		5mm Crystal Diameter	10mm Crystal Diameter
Mild Steel Block	Width – 19mm	5949	5429	5444	0.0010888	5.74	22.96
Mild Steel Block	Depth – 19mm	5949	5429	5444	0.0010888	5.74	22.96
Mild Steel Block	Length – 80mm	5949	5797	5804	0.0011608	5.38	21.54
Brake Disc	Depth – 7mm	5949	5738	5804	0.0011608	5.38	21.54

Attenuation Coefficient

When a sound wave propagates through a medium, wave intensity depletes over distance; this can be attributed to scattering or absorption. Scattering refers to reflection of waves in directions other than its original direction of propagation. Whilst absorption occurs due to sound converting into heat, absorption increases with frequency where rapid oscillations lose larger quantities of energy (Grabendörfer, et al., 2013). The combination of absorption and scattering are referred to as ‘attenuation coefficient’ (figure 7) which changes between materials (Martin, 2010).

Attenuation Coefficient Calculations

$$A = A_0 e^{-az}$$

$$\log\left(\frac{A}{A_0}\right) = -az$$

$$\frac{\log\left(\frac{A}{A_0}\right)}{z} = -a \quad \left(\frac{\text{Napers}}{\text{mm}}\right)$$

Where:
A = Attenuated signal
A0 = Un-attenuated signal
-a = Attenuation Coefficient
z = Distance travelled

$$\frac{\log\left(\frac{A}{A_0}\right)}{z} = -a \quad \left(\frac{\text{Napers}}{\text{mm}}\right)$$

→

$$20\log_{10}\left(\frac{A}{A_0}\right) = -az$$

$$\frac{20\log_{10}\left(\frac{A}{A_0}\right)}{z} = -a \quad \left(\frac{\text{dB}}{\text{length}}\right)$$

Figure 7: Formula Rearrangement for Attenuation Coefficient.

With multiple measurements taken, an average for distance and echo height percentage can be used to calculate attenuation coefficient (table 4). Equation 10 examples the calculation for echoes 1-2 for steel block width.

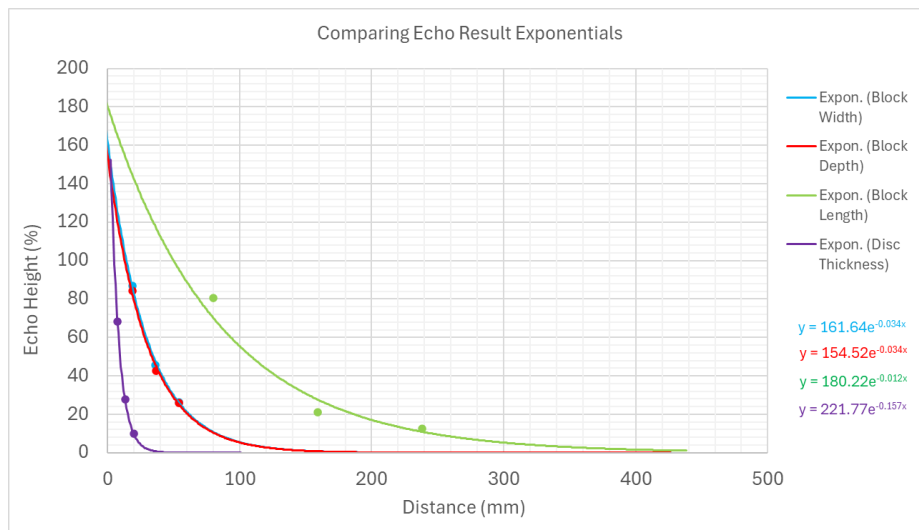
$$\frac{20\log_{10}\left(\frac{45.44}{87}\right)}{2 \times 19 \text{ mm}} = -0.148 \frac{\text{dB}}{\text{mm}} \quad (10)$$

Table 4: Components 5MHz Attenuation Coefficients.

Component	Dimension	Echo 1-2 dB/mm	Echo 2-3 dB/mm	Echo 1-3 dB/mm	Average dB/mm
Steel Block	Width (19mm)	-0.1484	-0.1238	-0.1361	-0.136
Steel Block	Depth (19mm)	-0.1568	-0.1141	-0.1355	-0.135
Steel Block	Length (80mm)	-0.0729	-0.0282	-0.0506	-0.051
Brake Disc	Depth (7mm)	-0.5568	-0.6406	-0.5987	-0.599

Results and Discussion:

From A-scan echo and distance data collected in practical laboratory exercise, averages of these two data points were collected and plotted (graph 11). Using exponential regression analysis, a trendline can be applied to each component and orientation, differences in trendlines represent rate of decay for echo height. Due to variations in metal granular structures, scattering quantities and therefore attenuation varies between materials and components of identical materials. Internal stress and impurities also effect attenuation where measuring and predicting these aspects prove challenging but vital to gaining accurate coefficients (Grabendörfer, et al., 2013).



Graph 11: Interpolating Echo Exponential Results

Differences between width and depth of steel block is minimal, this can be attributed to systematic measuring errors and grain boundary orientations. Systematic errors occur from operator error when using vernier callipers, error size is estimated at $\pm 0.25\text{mm}$ (Szczepinski & Kotulski, 2010). This therefore impacts velocity accuracy; with additional lack of velocity calibration this error increases. Exclusion of couplants from equations and calculations neglects reflected energy when transferring between medium boundaries. Due to near field, results for brake disc have a greater possibility for larger error as waves have not fully constructed in shorter distances. To overcome this, a probe with a smaller crystal diameter and/or frequency can be used. The combination of rough surfaces and corrosion cause a jagged and wider effect on echo results where reflections have travelled further based on trigonometry. An unsuitable probe type is also presented when testing along mild steel block length, where beam spread of a standard probe causes waves to reflect off internal walls and corners. By using a focused lens (figure 8 left), the beam can be focused on a specific point within a small area, increasing accuracy (Schirru, 2017).

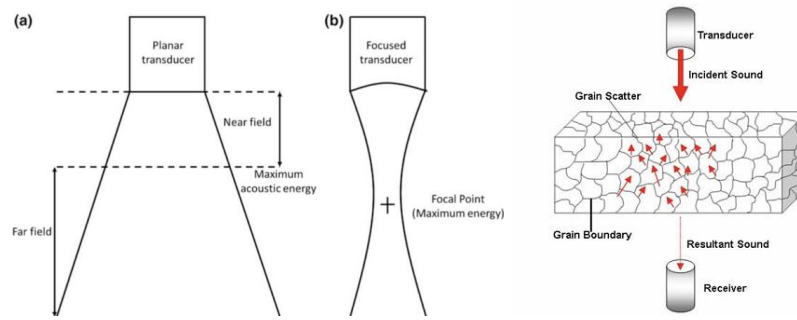
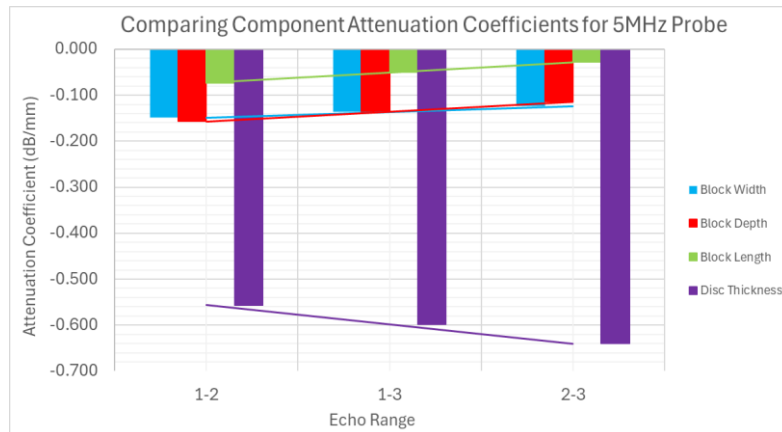
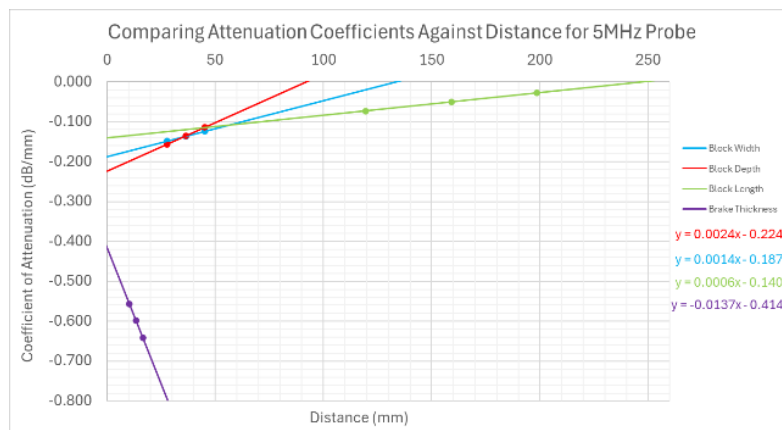


Figure 8: Transducer Types (Schirru, 2017) and grain boundary scattering (Berke, 2009).

The attenuation coefficients are calculated at 5 MHz, where steel block is lowest (0.135-0.136dB/mm), and brake disc highest (0.599dB/mm). Material thickness and component orientation also contribute to attenuation where steel block length has lowest absolute attenuation coefficient. Graph 12 compares results for each echo range, all follow a linear reduction in attenuation except brake disc. Interpolation of this data can be expressed linearly due to expression of decibel scale logarithmically (Johnson, et al., 2000), yielding graph 13. Similar effects between attenuation coefficient and lower frequencies (less than 10MHz) are expected, providing scattering losses are negligible (Chen, 2007).

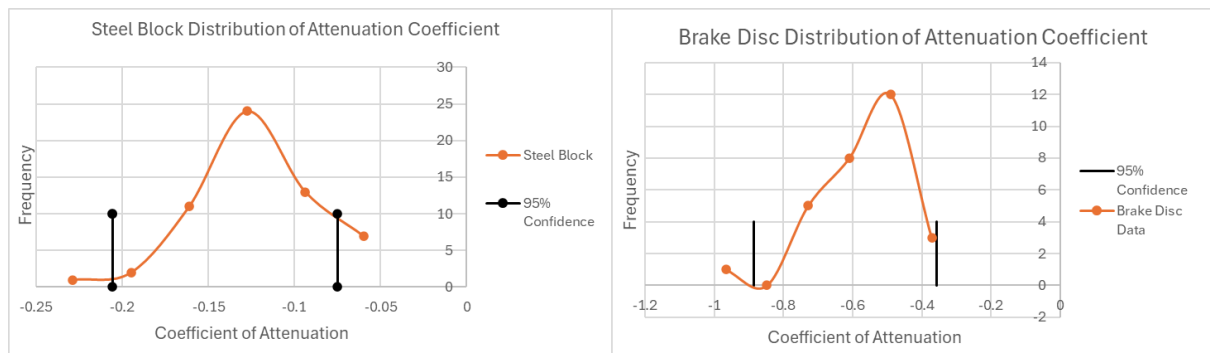


Graph 12: Attenuation Coefficient Bar Chart.



Graph 13: Interpolation of Attenuation Over Distance.

According to Ono, K (2020) mild steel has an attenuation coefficient of 0.1111-0.145dB/mm (depending on finishing process and carbon composition) and ductile cast iron 0.5925dB/mm. This is consistent with experiment data, indicating reliable results. Without technical data of component materials, it is difficult to approximate true composition and finishing method due to errors and uncertainties. The brake disc results however, are approximately 0.0065dB/mm apart (1.1%) indicating component is made from ductile cast iron, a common material for brake discs prone to abnormal wear and heating due to low surface hardness (Dixcel, 2023). This supports ultrasonic testing results where abnormal wear consisted of surface roughness and variations in component thickness. Final validation evidence is figure 8 (right), where Berke, M (2009) states cast components have a non-uniform grain structure increasing scattering, therefore attenuation. Distribution plots (graph 14) show steel block has a smaller 95% confidence range suggesting results are more accurate than brake disc.



Graph 14: Attenuation Coefficient Distributions.

Conclusion:

In conclusion, results have expected trendlines and suitable attenuation coefficients that closely match other sources based on material types. The brake disc had a significantly higher coefficient for a 5MHz probe at 0.599dB/mm than mild steel block (0.135dB/mm). A higher coefficient is due to greater variance in non-uniform grain structure and increased scattering. During this experiment certain assumptions, lack of calibration and systematic errors reduce accuracy and validity of results. Further suggestions to eliminate/reduce these errors: correctly calibrate velocity, account for couplants in calculations, utilise different probe types and crystal diameters.

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