

MSc Motorsport Engineering

Structural Integrity & Material Evaluation

<i>Assessment Title</i>	Ultrasonic Attenuation Coefficient Determination and Probability of Sizing Analysis
<i>Module Number</i>	ACEA7013
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Abstract

The application of ultrasonic non-destructive testing techniques to evaluate material properties and structural integrity forms the basis of this study. Emphasis has been put on determining ultrasonic attenuation coefficients and carrying out sizing assessments of defects by multiple technicians using a 5-MHz ultrasonic flaw detector. Key methodological approaches involved in time of flight, linear regression, bias and precision and root mean square error statistical techniques. The results of the tests indicated that there was a huge variation in the measurements for the operators 4 and 8 were the most reliable, while operator 10 had the largest bias and error. It was stated that the limitation of calibration in the ultrasonic equipment may be a source of systematic inaccuracies of procedures, and training for the operators are necessary to improve reliability and consistency during the ultrasonic testing. The above findings highlight that addressing both equipment and human factors has a great bearing on improving defect detection and material evaluation practices.

Apparatus

Mild steel block

Brake Disc

Silverwing Dscan 705 digital ultrasonic flaw detector

5 MHz zero-degree probe

Vernier caliper

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List of Symbols

Nomenclature

a [dB/mm]	Ultrasonic attenuation coefficient
A [m^2]	Area of which heat transfer occurs
C [/]	Constant
CV [/]	Coefficient of variance
d [m]	Distance
D [mm]	Crystal diameter
e [/]	Napier's constant
f [Hz]	Frequency
K [$N/m^2 \cdot p$]	Stiffness of material
N [/]	Total number of samples
NF [mm]	Near field
t [s]	Time of flight
T [K]	Temperature
V [m/s]	Velocity
$\bar{x}$ [/]	mean average
x_i [/]	Individual population value
Z [$Kg / m^2 \cdot s$]	Acoustic impedance
η [/]	
ρ [kg / m^3]	Material density
σ [/]	Standard Deviation
Σ [/]	Sum of
λ [m]	Wavelength

Introduction

Ultrasonic Non-Destructive Testing The ultrasonic NDT system is a non-contact and non-destructive technique that probes into material properties using high-frequency mechanical waves. It is a useful method to find an internal flaw, thickness, characterise materials. Two modes of ultrasonic NDT systems exist, these are pulse-echo and through transmission. To generate or detect ultrasonic waves, the need for an ultrasonic transducer arises. Therefore, the higher the frequency, the smaller flaws detectable, but depth penetration will be reduced.

Ultrasonic waves are acoustic waves with frequencies higher than the human audible limit, typically in the range of 20 kHz to 25 MHz. These high-frequency waves find extensive use in NDE applications because they are capable of traveling through gases, liquids, and solids.

Whenever an ultrasonic wave encounters a boundary between materials of different acoustic impedances, a portion of the wave energy will be reflected. This phenomenon will take place irrespective of material states such as solid-to-liquid, solid-to-gas, and even within a single solid in the presence of cracks, voids, or other discontinuities. These internal features create interfaces that reflect ultrasonic energy just like the external surfaces of the material.

The size, location, and severity of internal features can be gauged through the analysis of the reflected waveforms. This ability constitutes ultrasonic testing as one of the most vital techniques in defect detection and characterization within engineering materials and components. The accuracy and versatility of ultrasonic techniques guarantee their extensive application in such fields as aerospace, manufacturing, and civil infrastructure for material integrity and structural reliability.

Calibration

To get verifiable and repeatable results that can be accurately compared to other measured results from other machines it should be calibrated, however due to limitations it was not calibrated for the test. This means that the machine is likely to be under or overestimating results at a fixed rate. Due to the length of time from which the machine was last calibrated, comparison accuracy is likely to be inaccurate. The last calibration sticker for the ultrasonic testing device can be seen in figure 1.

It can still be used for taking measurements as accuracy is not detrimental to the outcome in this case although it will account for some inaccuracy, however if it were for components that were in use it is recommended that machine is calibrated.



Figure 1 - Calibration sticker for Ultrasonic testing machine

Time of flight theory

The principle of time-of-flight theory is the time it takes for an object or signal to travel from one point to another and is determined by its speed and distance covered. As described by equation 1. It is used in ultrasonic testing to determine the location of discontinuities in a part by accurately measuring the time taken for the soundwave produced by the transducer to travel through the thickness of the material and reflect from the back of the material and return to the transducer. The time is divided by two to account for the travel from transducer to the back of the material and the reflection.

$$t = \frac{d}{v} \quad [1]$$

Ultrasonic Attenuation Coefficient Determination

From the recorded results, the ultrasonic attenuation coefficient can be determined using the following formula, equation 2.

$$A = A_0 e^{-\alpha z} \quad [2]$$

$$-\alpha \left(\frac{\text{napers}}{\text{mm}} \right) = \frac{\log\left(\frac{A}{A_0}\right)}{z} \quad [3]$$

It can be rearranged to be adapted for pressure, changing the units from napers/mm to dB/mm as that is the units for the energy within a soundwave and what will be used throughout.

$$-\alpha = \frac{20 \log_{10}\left(\frac{A}{A_0}\right)}{z} \quad [4]$$

Determining the attenuation coefficient is important as it affects the detection of flaws (Ono K, 2020), a high coefficient can obscure the signal of small defects. Attenuation measurements are important to assess the integrity of the structures, such as variations in attenuation can indicate that degradation and damage over time has occurred. This can lead to preventative maintenance of components, lowering operational costs or avoiding complete failure of a critical component.

Variations in attenuation can be caused by crack formation, porosity development and grain growth and phase changes. Damage such as cracks can cause ultrasound waves to scatter due to the change in acoustic impedance (Regtien, P. and Dertien, E. 2022), due to the crack being filled with air or a vacuum. Both have an acoustic impedance of nearly 0 compared to the surrounding material, this means that the ultrasonic waves are reflected or scattered. If the crack

is otherwise filled with another fluid, there is a less significant change in acoustic impedance (Farhat, H. 2021) , leading to some ultrasonic waves to be transmitted and some reflected.

When the grain size is smaller than the wavelength, attenuation is not affected much, however, as the grain size approaches or exceeds the wavelength, scattering becomes more significant, with larger grains causing more scattering, increasing attenuation. Geometry and orientation of cracks can also cause the ultrasonic waves to scatter, the soundwave can be scattered in multiple direction.(Cook, DA *et al* 2001)

$$\lambda \text{ Wavelength} = \frac{V \text{ (Velocity)}}{f \text{ (frequency)}} \quad [5]$$

$$Z \text{ (Acoustic impedance)} = \rho \text{ (material density)} \cdot V \text{ (velocity)} \quad [6]$$

Dead, near and far field zones

When conducting ultrasonic NDT tests, measurements should be made in the far field due to the sound pressure varying so much because of diffraction effects. Diffraction effects are caused by material boundaries, internal flaws, surface roughness and geometric features. The features can all create complex patterns of constructive and destructive interference.

$$\text{Near Field} = \frac{D^2}{4\lambda} \quad [7]$$

$$\text{Near Field} = \frac{8.9^2}{4 \cdot 1.113} = 17.792 \text{ mm}$$

17.792mm is the start of the near field, based on the calculation above. Beyond this point the results are useable and can be reliability analysed. If the defects were believed to be in a lesser depth than the near field a higher frequency transducer could be used, a transducer with a smaller diameter or a spaced coupling with a known acoustic impedance could be used.

Reflected Energy

As previously stated, cracks in a material affect the acoustic impedance. The reflected energy can be calculated by using the acoustic impedance of the two materials, or by the material and whatever fluid fills the crack if known.

$$RE \% = \left(\frac{z_1 - z_2}{z_1 + z_2} \right)^2 \cdot 100 \quad [8]$$

$$RE \% = \left(\frac{46.7 - (4 \cdot 10^{-4})}{46.7 + (4 \cdot 10^{-4})} \right)^2 \cdot 100 = 99.9966\% \quad [9]$$

Therefore a mild steel block with a crack filled with air it would reflect 99.99% of energy, based on the calculation with very little energy being absorbed by the air due to the very low acoustic impedance of the air. The acoustic impedance values for mild steel and air were obtained from a material properties sheet.

Viscoelastic losses (internal friction)

Mild steel exhibits internal friction, a property that resists the motion of atoms as they oscillate under applied stress. This friction results in the conversion of a portion of the mechanical energy into heat, leading to attenuation of the propagating ultrasonic waves.

The degree of attenuation in mild steel is influenced by viscoelastic losses, which depend on the frequency of the acoustic waves. At higher frequencies, the increased atomic motion generates greater internal friction, thereby causing greater attenuation of the ultrasonic energy. This relationship between frequency and attenuation must be carefully considered in ultrasonic testing applications to optimize inspection accuracy and ensure reliable material characterization.

$$\alpha = \frac{\pi f}{V} \left(\frac{\eta}{\rho} \right) \quad [10]$$

Scattering

Scattering occurs when the acoustic waves interact with inhomogeneities such as microstructural features such as grains, defects and inclusions within the mild steel. These irregularities result in the scattering of a portion of the ultrasonic wave due to variations in at the interfaces. Scattering is affected by variations in grain size, phase boundaries, impurities or voids in the material. The larger and more varied the microstructure the more scattering will occur.

Rayleigh scattering

Rayleigh scattering occurs when the wavelength of the ultrasonic wave is much larger than the size of the scattering particles or imperfections in the material. This type of scattering primarily contributes to ultrasonic attenuation in materials with fine grain structures. The attenuation coefficient due to Rayleigh scattering is given by equation 10.

$$\alpha \propto f^4 \quad [11]$$

Absorption

Absorption is the process by which the energy of acoustic waves is converted into heat as they propagate through the steel. Atomic vibrations or dislocations in the lattice structure absorb

energy from the propagating waves, which contributes to the attenuation, this mechanism becomes more significant at higher frequencies.

The attenuation mechanisms in mild steel are influenced by both the intrinsic properties of the material, such as its grain structure and composition, as well as external factors, including temperature, negligible at most temperatures (Menning, K. 2009), and wave frequency.

Method

Two sample materials were provided to determine the material attenuation coefficient values using time of flight methods. Ultrasonic flaw detection was the designated choice, due to the equipment available. A Zero-degree 5Mhz probe was used on a mild steel rectangular block and a used brake disc. The probe was connected to the ultrasonic tester cord, an unspecified gel was applied as medium between the probe and material for the transmission of mechanical waves acting as an acoustic coupling. Temperature in the room was not recorded, as it has a negligible effect on acoustic impedance of fluids. Each material was laid on a flat smooth table, when measurements were taken to keep consistency.

Before measurements were taken, a vernier caliper was used to measure the length and width of the mild steel block. Gel was applied to the surface before measurements were taken, 10 measurements were taken from the side and 5 were taken from the length. Before moving on to the brake disc.

The brake disc was more difficult to get measurements from due to rust and the vents between the working surfaces. In the end the measurements were taken from brake disc hub, where 10 measurements were taken. The results for all measurements were recorded, alongside the amplitude, velocity and distance.

Initial wave amplitude set to 80% is a calibration point, using the gain function on the ultrasonic device. The velocity was originally set to the recommended velocity from the material sheet, which suggested a velocity of 5960 m/s. This was deemed too high of a velocity which was then reduced to 5564 m/s to account for the material not being an exact replication of mild steel. This was done by comparing the distance the soundwave travelled against the measured length from the vernier caliper, this was to ensure that the machine was accurate enough to take repeatable results. A similar process was used for the brake disc, with the velocity being adjusted to 3714 m/s.

Ultrasonic non-destructive testing can be used to detect internal flaws, measure thickness and characterise materials. There are two main types, pulse-echo and through-transmission. Ultrasonic refers to a frequency higher than the human audible range, generally consisting of frequencies between 20KHz and 25MHz. The directed energy in an ultrasonic wave is reflected by boundaries between materials, regardless of whether the material is a gas, liquid or solid. Ultrasonic waves are also reflected by any cracks or voids in a solid material, the reflected waves can be compared to the reflected waves from the external surfaces enabling the size and severity of the internal features to be identified.

Generating and detecting ultrasonic waves requires an ultrasonic transducer. The higher the frequency, the smaller the flaws that can be detected however the depth of penetration will be decreased.

As figure 2 and 3 show, the amplitude decreases for echo, this is because of the attenuation, and the beam spread

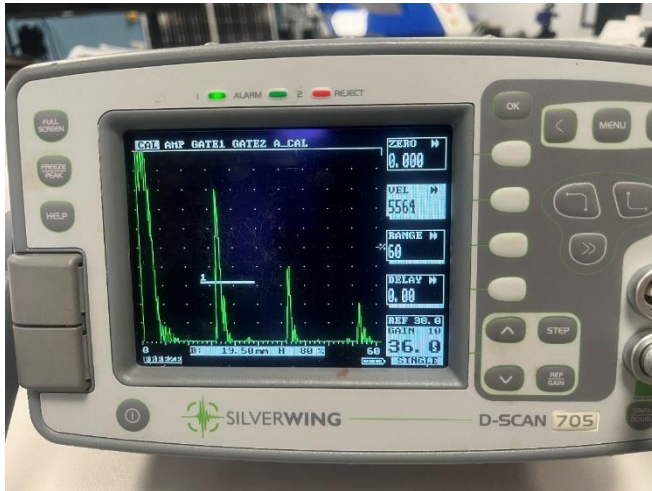


Figure 2 - Velocity of mild steel block when tested

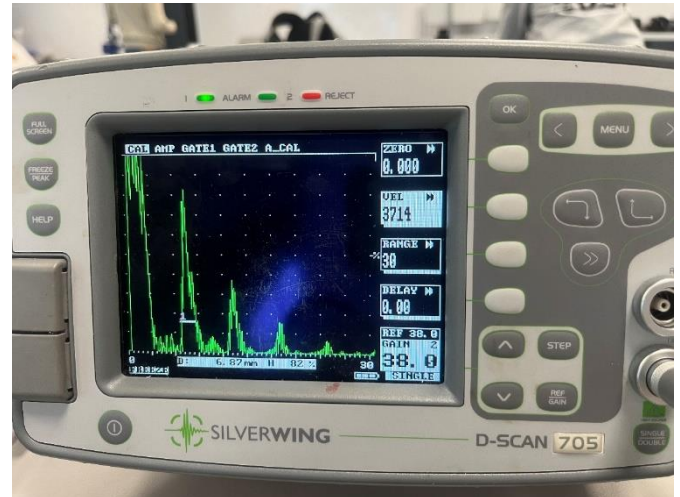


Figure 3 - Velocity of brake disc when tested

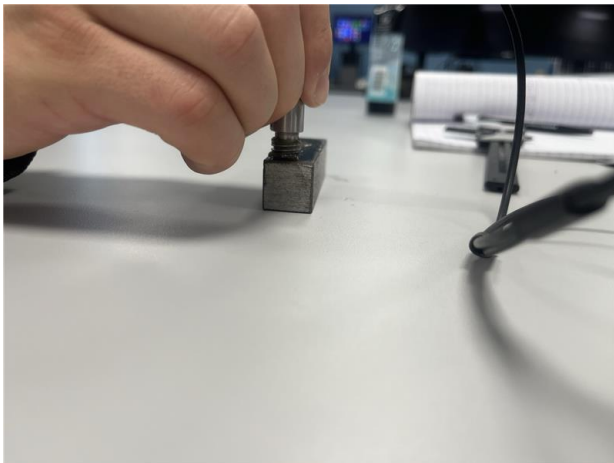


Figure 5 - Testing mild steel block width



Figure 4 - Testing mild steel block length



Figure 6 - mild steel block width

Through Wall Sizing Accuracy analysis

Introduction

A set of data was given, that was to be analysed using linear regression and statistical methods. The data can be seen in figure 7, where 21 defects were measured by 10 technicians, with the true defect sizes given to make a comparison using the aforementioned methods.

Measurements and method

To analyse the measured data two techniques were used. Linear regression and statistical methods in excel. There was an analysis of 10 technicians that measured 21 defects each, with a comparison being made between the 10 technicians and true measurements to determine the accuracy and confidence of the results. The true measurements and the technicians' measurements can be seen in figure 7. The analysis was done using Excel and MATLAB, with graphs being created in both to provide a clear analysis. Analysis started with linear regression where all the operator's data was plotted against the true size values, a trendline was plotted and the equation given in the format of equation 12, was used to plot

$$y = mx + c \quad [12]$$

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 7 - Through wall sizing data

Linear Regression

To analyse the measured data for each operator is plotted against the true values, with a trendline added to the graph. The equation for the linear trend line is given by excel in the format of the following equation 11, alongside the R^2 value. The R^2 value shows the variance within the data, the smaller the value the closer the data values are together. The equation for the trendline is used to determine the linear relationship between the measured and true sizes. True size is plotted against the x axis and the estimated size is plotted against the y axis. The equation produced from the trendline is then used to plot a line on a separate to be able to compare to the true sizes of the defects. Alongside plotting $\pm 0.5\text{mm}$ and $\pm 1\text{mm}$ to see how far the results vary from the trendline as seen in figure 9.

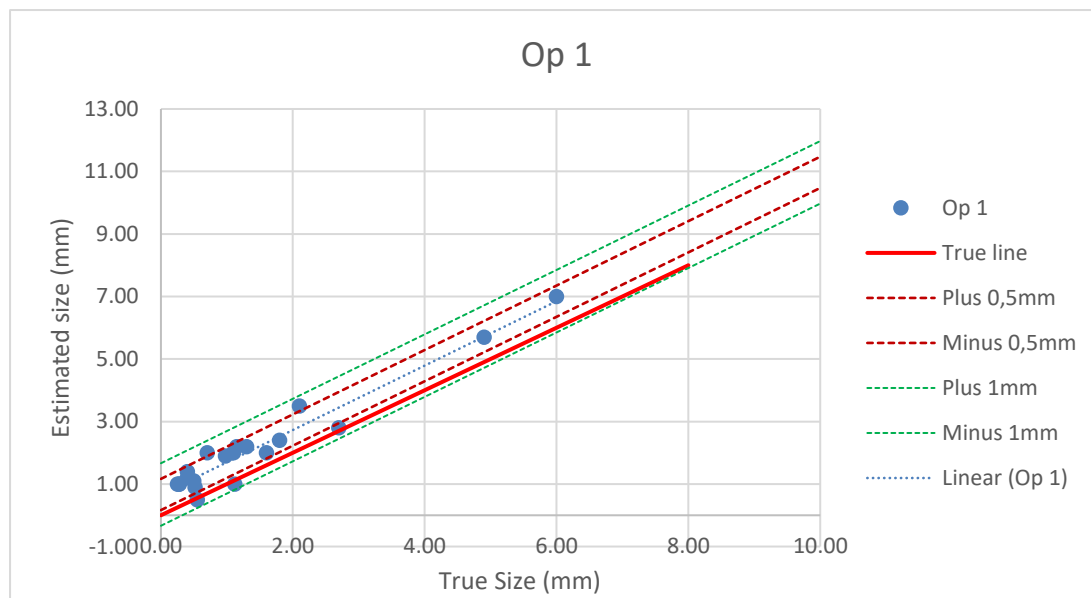


Figure 8 - Linear regression

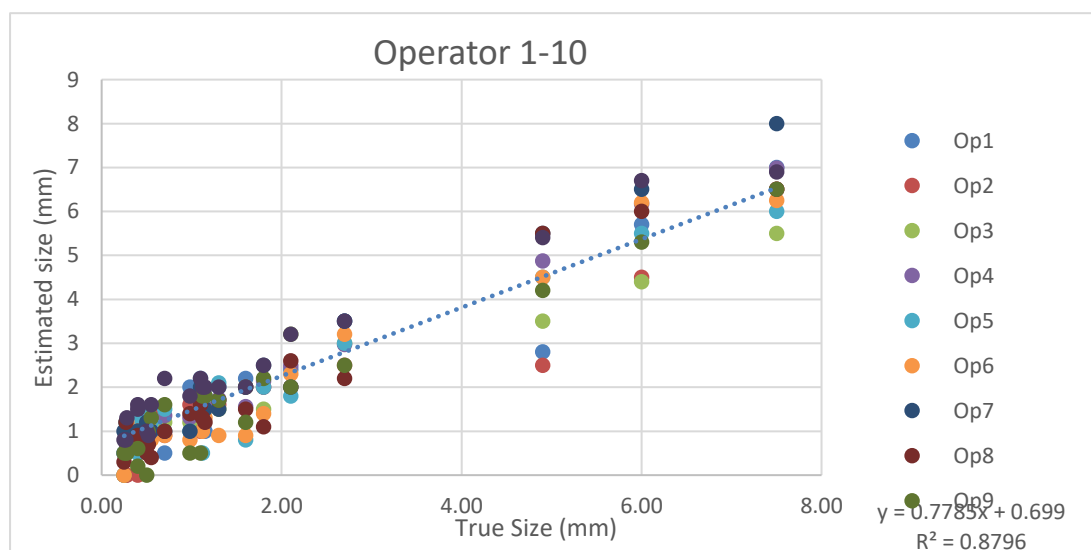


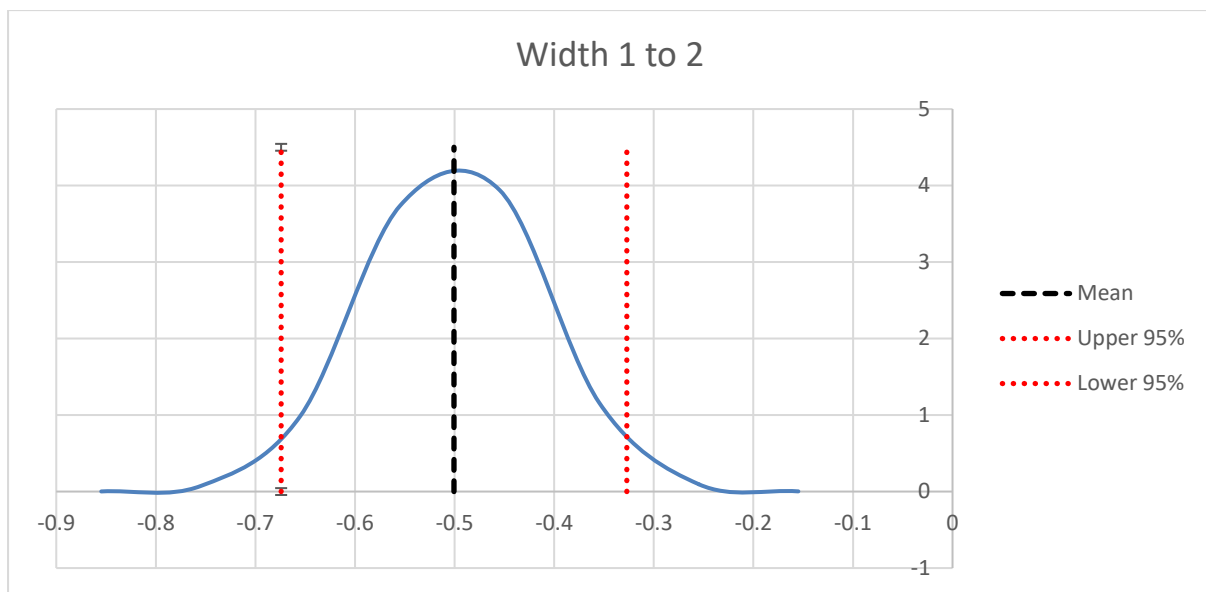
Figure 9 - True size vs estimated size Op1

Statistical Analysis

Standard deviation (σ)

Statistical analysis uses standard deviation (σ) to determine the variance of the data from the mean. The formula is shown in equation 13.

$$\sigma = \sqrt{\frac{\sum (x_i - \mu)^2}{N}} \quad [13]$$



95% confidence limits were plotted on a bell curve, all figures for the brake disc and steel block were contained within the limits. The confidence limits were calculated using equation 14.

$$95\% \text{ confidence} = \bar{x} \pm 1.96 \cdot \sigma \quad [14]$$

Coefficient of variance (CV)

The coefficient of variance shows the relative size of the standard deviation compared to the mean. Allowing operators to be compared to each other. Coefficient of variance percentage can be calculated using equation 15.

$$CV \% = \frac{\sigma}{\mu} \cdot 100 \quad [15]$$

The coefficient of variance is quite large, which is to be expected, based on the data set. A high CV value is expected due to the difference in operators with human error, the reliability of the data is unknown, and the equipment used is unknown. Therefore, the results of the test cannot be considered reliable.

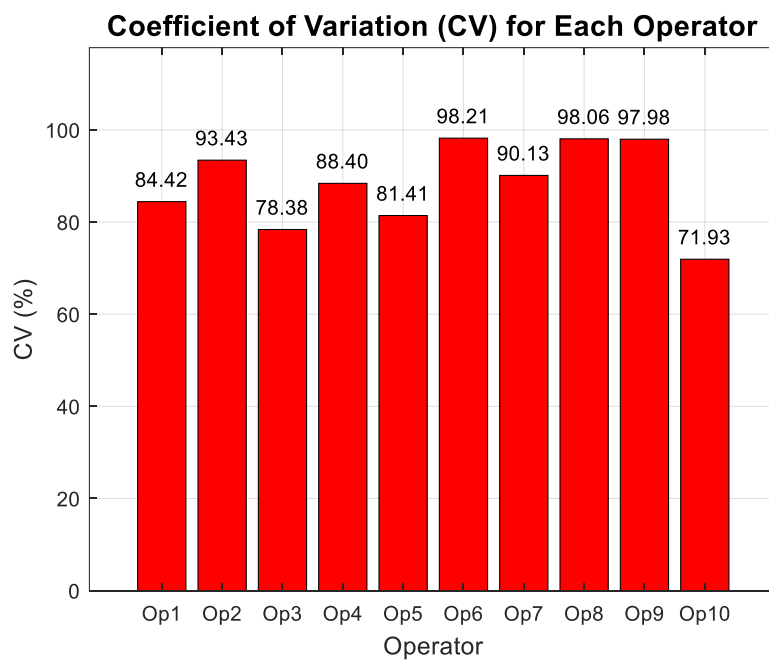


Figure 10 - Coefficient of Variation for each operator

Root mean square error (RMSE)

RMSE is a way of assessing the accuracy of results by calculating how far away the measured results are from the actual results. The formula for RMSE is given in equation 16, which is used to calculate the numbers in figure 10. For the RMSE, the lower the value the more accurate the recorded measurements, therefore operators 4 and 8 have the most accurate measurements when compared to the actual results in this instance but overall may not be the best.

$$RMSE = \sqrt{\frac{1}{n} \sum_{i=1}^n (y_i - \hat{y}_i)^2} \quad [16]$$

Operator 1 RMSE:	0.7992
Operator 2 RMSE:	0.5452
Operator 3 RMSE:	0.6556
Operator 4 RMSE:	0.4037
Operator 5 RMSE:	0.6920
Operator 6 RMSE:	0.5067
Operator 7 RMSE:	0.5616
Operator 8 RMSE:	0.4670
Operator 9 RMSE:	0.5382
Operator 10 RMSE:	0.8588

Figure 11 - Root Mean Square Error results

Bland-Altman Plot

The Bland-Altman plot is a graphical method used to evaluate the agreement between two measurement methods by analysing their bias and precision (Giavarina, D. 2015). The plot displays the differences between paired measurements on the y-axis against their averages on the x-axis, allowing a visual assessment of whether differences vary across the range of measurements. The bias, or mean difference, is represented as a horizontal line, providing an estimate of the systematic difference between the two methods. The precision is showed through the spread of data points around the bias line, typically quantified by the limits of agreement (LOA), defined as the bias ± 1.96 times the standard deviation of the differences. A narrow LOA indicates high precision, while wide limits suggest greater variability. By examining both bias and precision, the Bland-Altman plot helps determine if the two methods can be used interchangeably or if discrepancies are clinically significant. The ± 1.96 acts as the 95% confidence line in this case, showing that there are outliers within the data set.

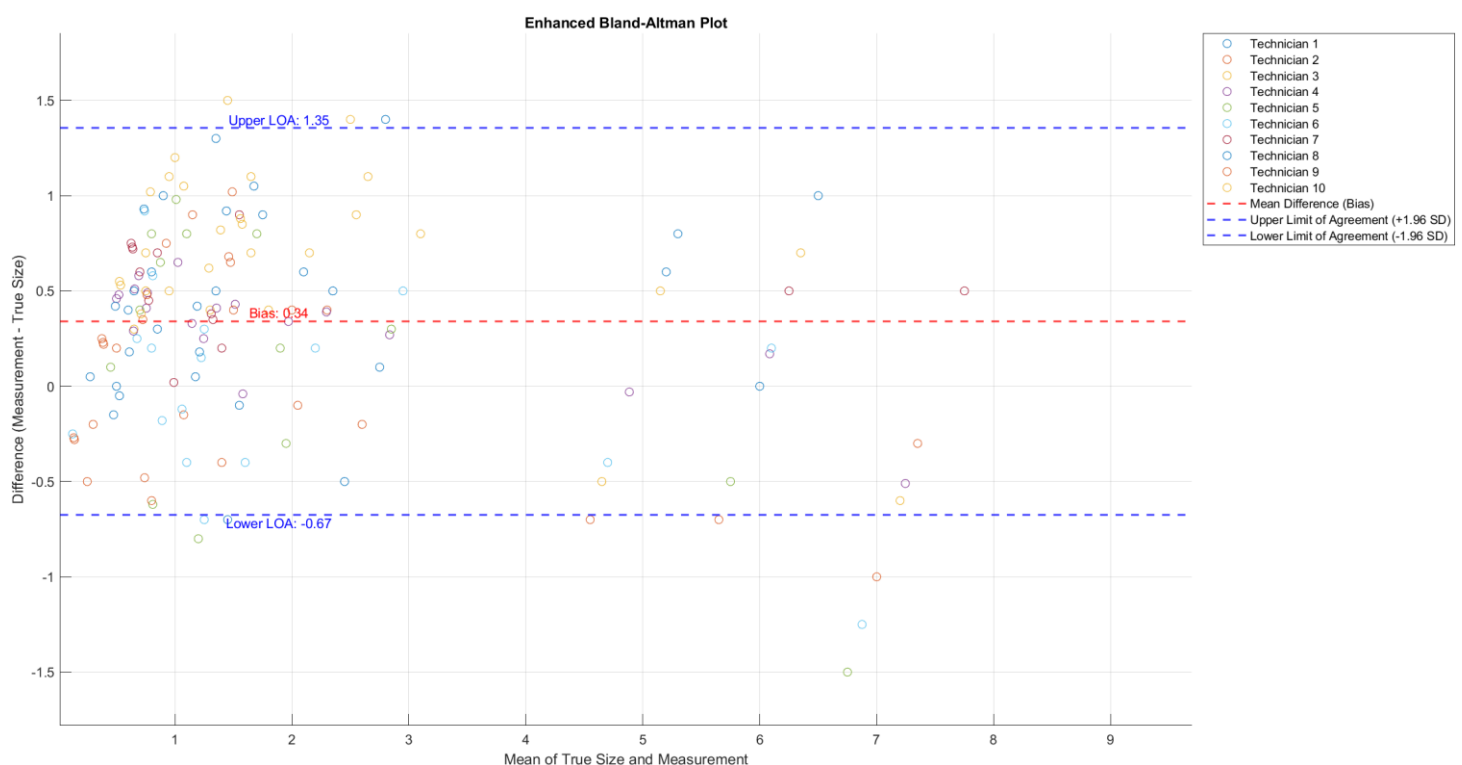


Figure 12 - Bland-Altman Plot

Bias measures the deviation of the average measurement from the true sizes within the data set. Bias gives an indication of how far away from the true size, the measured values are on average. A large bias means that there is a consistent overestimation or underestimation depending on the results.

Precision is the repeatability of the measurements, with no relation to the closeness to the true value. A high precision means that the results are reproducible even if the results are biased or inaccurate.

RMSE emphasises larger errors more than small errors due to squaring. The data below is plotted on the graph in figure 13.

Technician	Bias	Precision	RMSE
1	0.69905	0.39699	0.79923
2	0.30857	0.46057	0.5452
3	0.38952	0.54036	0.6556
4	0.31571	0.25779	0.40369
5	0.20857	0.67611	0.692
6	0.072857	0.51386	0.50674
7	0.50381	0.25433	0.56163
8	0.1419	0.45591	0.46701
9	0.013333	0.55128	0.53816
10	0.75143	0.42617	0.85885

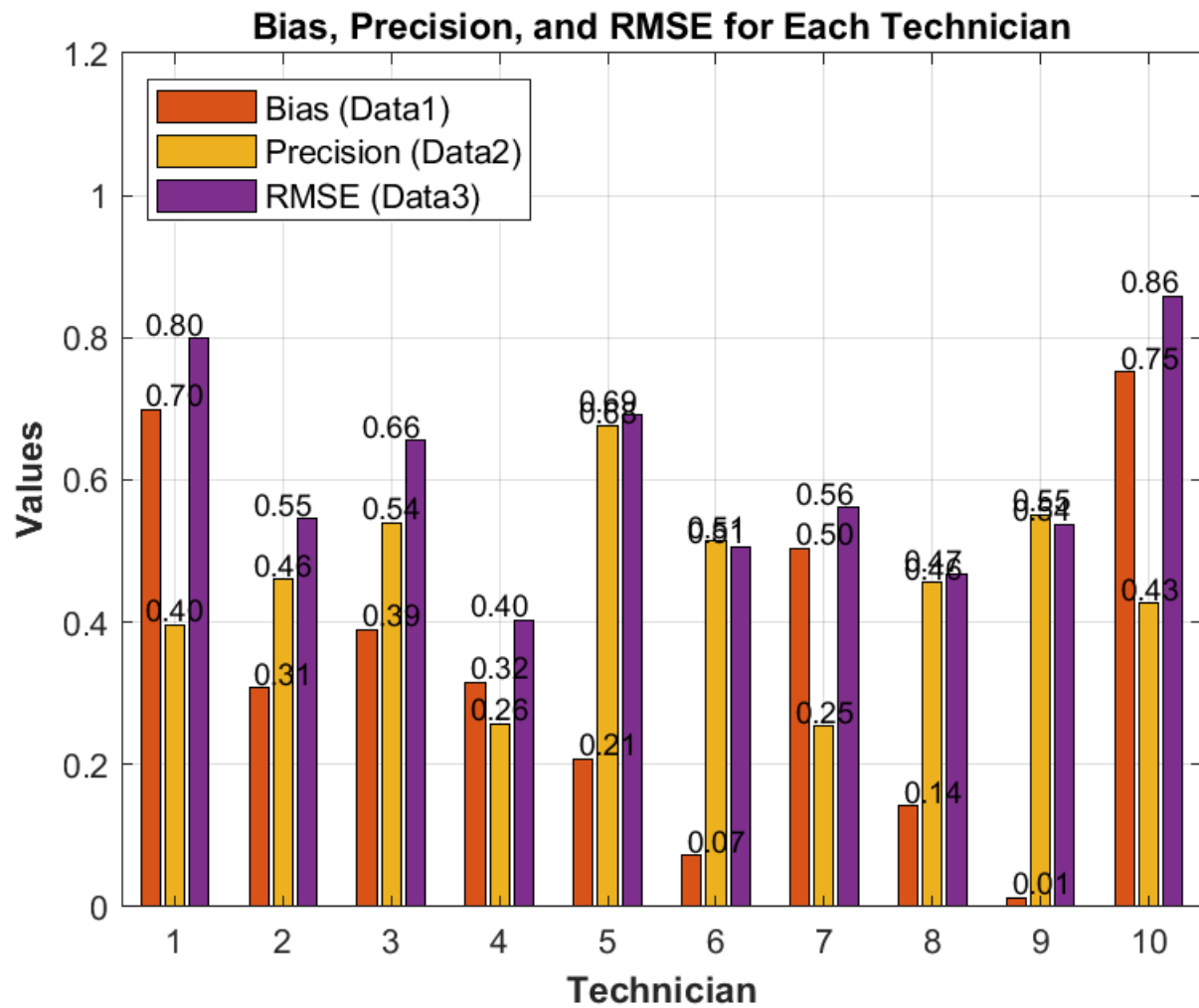


Figure 13 - Bias, Precision and RMSE

Conclusion

The ultrasonic tests and data analysis conducted during the study highlighted the effectiveness and problems regarding the assessment of multiple technicians for defect sizing. Quantitative insights into the variability and reliability of the measurement could be provided through linear regression analysis, Bland-Altman plots, and statistical metrics in terms of bias, precision and RMSE

Accordingly, the smallest RMSE values were associated with operators 4 and 8, which showed more reliable defect size measurements. Correspondingly, operator 10 gave the highest bias and RMSE, indicating overestimation in measurement on many occasions. Although a consistent overestimation is not an issue, because it can be solved later by stating that the defect is likely to be below that size or that depth and that is likely to be the maximum value. Significant reliability in both bias and precision across operators in present study shows individual differences in technique, which may demand further training and calibration of equipment.

The methodology was again shown to be capable of the detection and sizing of defects, although some inconsistencies among operators, again possibly down to lack of training or equipment. The systematic errors possibly came from calibration problems with the ultrasonic equipment. These results show that well-calibrated equipment, standardised procedures and operator training are the most important ways to improve the reliability of the measurements, reducing variability. Such factors will help in further improving the accuracy of ultrasonic testing in defect detection and material evaluation.

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