



Prifysgol Cymru
Y Drindod Dewi Sant
University of Wales
Trinity Saint David

MSc Motorsport Engineering

Part 1

<i>Assessment Title</i>	Ultrasonic Attenuation Coefficient Determination and Probability of Sizing Analysis
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<i>Student Number</i>	2306046
<i>Student Name</i>	Roland Magyar
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Abstract

Through the report, it shows the investigation of ultrasonic non-destructive testing on a rectangle steel block and an old brake disc to find the attenuation coefficients. The measurements were conducted using an ultrasonic flaw detector. The results of the experiment showed key challenges, including errors due to equipment calibration, human error as well as material surface finishes. Even with these issues, the attenuation coefficient was successfully calculated for the steel block showing how the method can be useful. Recommendations for improving the test and making it more reliable included machine calibration, training to use equipment and surface finish improvements.

1.Apparatus

- Vernier Calliper
- Zero-degree 5MHz Probe
- Brake disc
- Steel block
- Ultra sonic flaw detector (Silverwing D-scan 705) Figure 1
- Coupling



Figure 1: Ultra-Sonic Flaw Detector

2.Introduction

Ultrasonic non-destructive testing is a widely used process to help find flaws internally as well as the structural integrity of the material. The report is aimed around the attenuation coefficient, two components were sampled one being a rectangle steel block and the other being a brake disc, these components were chosen to see how accurate the ultrasonic testing can be. The data collected is analysed to see where the imperfections such as cracks or voids could be alongside discussing potential errors and ways of improving for future tests.

During the investigation, key steps are included like velocity adjustments specific to the material but also the use of coupling agents to enhance the energy transfer when using the equipment of an ultrasonic flaw detector with a 5MHz probe.

3.Method/Procedure

The approach taken to determine the attenuation coefficient of two steel samples is given in this section. The first sample is a rectangular steel block with dimensions of 19mm by 80mm in length as seen in Figure 2. The second sample is a used brake disc where measurements were taken from the central hub of the brake disc measuring 21mm in thickness as seen in Figure 3. A minimum of 10 measurements are taken for each sample and averaged to compensate for variation in the material structure. Each component is measured so that the velocity of sound in the material can be set on the UT set. This is important as for each type of material the settings are different, and this effects the results.

- Component measurements taken using a vernier calliper
- Check machine calibration and set up
- Gel applied to the component surface
- Prob held and run over certain areas
- Measurements taken from flaw detector
- Process repeated to take multiple measurements



Figure 2: Steel Block

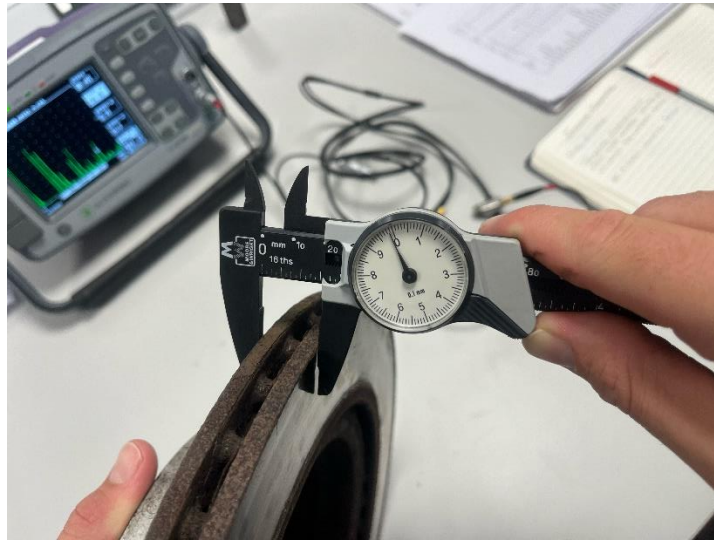


Figure 3: Brake Disc

The first step in ensuring the accuracy of the measurements is to verify that the ultrasonic flaw detector was properly calibrated. The last calibration date is shown in Figure 4. Proper calibration is critical to maintaining the reliability and precision of the equipment.



Figure 4: Calibration Proof

Following calibration verification, the machine's velocity and test range were configured. The velocity setting is dependent on the material being tested. To determine the appropriate velocity, reference is made to the ultrasonic velocity table, as shown in Figure 5. This table provides the necessary material-specific velocity values for the test settings.

Material Units	Velocity (C) m/s x 10 ³	Velocity (S) m/s x 10 ³	Density kg/m ³	Acoustic Impedance
Air	0.33	-	1.2	0.0004
Aluminium	6.40	3.13	2700	17.3
Barium Titanate A	5.26	-	5700	30.0
Barium Titanate B	5.53	-	5700	31.5
Beryllium	12.89	8.88	1800	23.2
Brass	4.37	2.10	8450	37.0
Cast Iron	3.5 to 5.6	2.2 to 3.2	7200	25 to 40
Copper	4.76	2.33	8930	42.5
Glass (Crown)	5.66	3.42	3000	17.4
Gold	3.24	1.20	19300	63.0
Iron	5.96	3.22	7850	46.8
Lead	2.40	0.79	11300	27.2
Lead Niobate	2.76	-	5800	16.0
Lead Zirconate Titanate A	3.00	-	7600	22.8
Lead Zirconate Titanate B	3.00	-	7500	22.5
Lithium Sulphate	5.45	-	2060	11.2
Magnesium	5.74	3.08	1720	9.90
Mercury	1.45	-	13550	19.6
Molybdenum	6.25	3.35	10200	63.7
Nickel	5.48	2.99	8850	48.5
Oil	1.44	-	900	1.3
Perspex	2.68	1.32	1200	3.2
Platinum	3.96	1.67	21400	85.0
Polystyrene	2.35	1.12	1060	2.5
Steel (Mild)	5.96	3.24	7850	46.7
Steel (Stainless)	5.74	3.13	7800	44.8
Silver	3.70	1.70	10500	36.9
Tin	3.38	1.61	7300	24.7
Titanium	5.99	3.12	4500	27.0
Tungsten	5.17	2.88	19300	100.0
Tungsten-Araldite	2.06	-	10500	21.65
Tungsten-Carbide	6.65	3.98	10000 to 15000	66.5 to 98.5
Uranium	3.37	2.02	18700	63
Water	1.48	-	1000	1.48
Zinc	4.17	2.48	7100	29.6
Zirconium	4.65	2.30	6400	29.8

Figure 5: Velocity Table

The range was configured based on the size of the material or component being tested. For the steel block, which was tested first, the range was set to 70. This value was selected as it is three times the width of the block, allowing the 3 echoes to be clearly displayed on the screen. This configuration ensured that the test results were both accurate and visually interpretable. This can be seen in Figure 6.

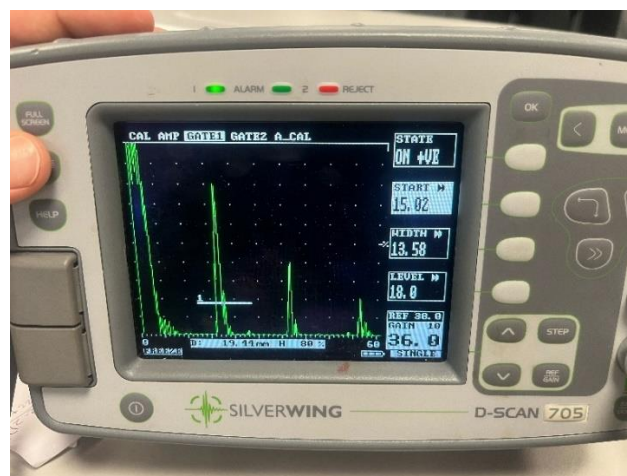


Figure 6: Echo Displays

Following the measurement of the material, a coupling agent was applied to the surface of the steel block to improve the acoustic impedance matching. This step was essential to maximise energy transfer during testing. In this instance, hair gel was used as the coupling agent. Once the coupling was applied, a 5 MHz probe was positioned on the surface of the steel block, as shown in Figure 7. The gain was adjusted to achieve approximately 80% amplitude, ensuring a gap on the screen that allowed the peak of the wave to be visible and this helps with accuracy throughout the test.

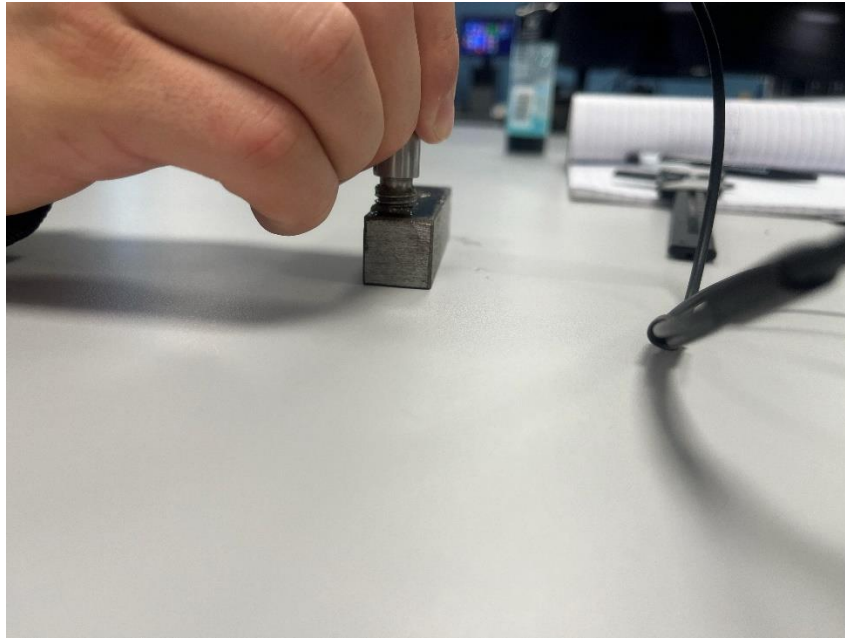


Figure 7: Probe Placement

Measurements were obtained from three echoes to enhance accuracy and ensure a comprehensive range of results. Multiple echoes also facilitated the detection of any potential defects within the steel block during the experiment. Once the measurements for the steel block were completed, the process was repeated to collect a broader range of data. After this the process was also repeated for the brake disc.

4. Measurements and Graphs of Raw measurements

The raw measurements obtained from the experiment are presented in the Table 1 And 2 below. The data includes multiple echoes, which represent the pulses transmitted and received by the ultrasonic detector.

Mild steel rectangular block							
Measurement		Echo 1		Echo 2		Echo 3	
		Distance (mm)	Amplitude (%)	Distance (mm)	Amplitude (%)	Distance (mm)	Amplitude (%)
Direction 1 (width)	1	19.44	80	37.68	40	55.67	20
	2	19.44	80	37.44	39	55.67	20
	3	19.45	91	37.44	45	55.67	26
	4	19.47	85	37.44	41	55.67	23
	5	19.47	81	37.44	39	55.67	22
	6	19.46	90	37.44	48	55.67	38
	7	19.47	81	37.44	41	55.67	27
	8	19.47	78	37.44	39	55.67	30
	9	19.50	78	37.68	40	55.67	26
	10	19.50	73	37.68	38	55.67	23
Mean		19.47	81.70	37.51	41.00	55.67	25.50
Direction 2 (length)	11	76.87	84	166.8	31	241.2	28
	12	76.81	82	165.6	47	241.2	30
	13	76.84	79	165.6	30	241.2	21
	14	76.84	90	166.8	24	242.4	17
	15	76.81	70	165.6	42	241.2	28
Mean		76.834	81	166.08	34.8	241.44	24.8

Table 1: Steel Block Measurements

As the detector emits a pulse, it reflects back to the probe after interacting with the material, then bounces away again, Consequently, the echoes diminish in amplitude each time. In the data, the measurement corresponds to the thickness of the material or component. For instance, as shown in Figure 8, the width of the steel block was measured to be 19.44 mm, amplitude represents the size of the wave displayed on the screen. The decrease in amplitude with each echo is attributed to the increasing distance travelled by the wave. Beam divergence is also a cause of decrease of amplitude this happens due to the ultrasonic wave propagating and the wave spreading out as it spreads out it reduces the amplitude of the reflected signal. (Iowa State University, 2024)



Figure 8: Block Width Measurement

Measurements on the brake disc were conducted on the hub section. This location was selected due to the disc being vented, which introduced air gaps that could interfere with results. Additionally, the presence of corrosion on the disc posed further complications during the measurement process. The results can be seen in the table presented below.

Brake disc hub						
Measurement	Echo 1		Echo 2		Echo 3	
	Distance (mm)	Amplitude (%)	Distance (mm)	Amplitude (%)	Distance (mm)	Amplitude (%)
1	6.87	80	12.84	37	18.96	15
2	7.22	75	12.96	29	19.20	11
3	7.22	76	12.96	35	19.08	16
4	6.82	74	12.84	29	18.84	10
5	6.92	75	12.96	26	19.20	8
6	6.92	71	12.96	32	19.08	14
7	7.22	74	12.84	31	18.96	12
8	6.92	72	12.96	30	19.08	11
9	6.87	75	12.84	34	18.72	15
10	6.85	74	12.72	36	18.72	16
11	6.81	80	12.60	40	18.60	17
12	6.84	91	12.60	54	18.60	26
13	7.22	73	12.84	39	18.84	20
14	6.87	82	12.72	41	18.72	20
15	7.20	75	12.84	27	18.96	9
Mean	6.98	76.47	12.83	34.67	18.90	14.67

Table 2: Brake Disc Measurements

5. Calculations and error estimates

Following the completion of the experiment, the attenuation coefficient was calculated for each echo. The attenuation coefficient represents the rate at which the material absorbs energy from the ultrasonic waves. These results can be seen in tables in the results section

The equations used can be seen below:

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

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

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

A = Attenuated signal

A_0 = Un – Attenuated Signal

$-a$ = attenuation Coefficient

Z = distance travelled

The calculation of the near field requires determining the wavelength of the ultrasonic waves. The wavelength is directly proportional to the velocity and inversely proportional to the frequency of the wave. As a result, the wavelength varies depending on the material being tested.

$$\text{Wavelength}(\lambda) = \frac{\text{Velocity}(v)}{\text{Frequency}(f)}$$

The near field equation, shown below, is used to determine the distance at which destructive interference occurs within the crystal. This interference can result in reduced measurement accuracy, making the identification of the near field critical.

$$NF = \frac{D^2}{4\lambda}$$

Where:

$NF = \text{NearField}$

$D = \text{Crystal Diameter}$

$\lambda = \text{Wavelength}$

The confidence level equation can be seen below this equation was used to show where the confidence levels were for the bell curves which will be seen later in the results section (Bobbitt, 2020)

$$\text{Confidence level} = \bar{x} \pm Z \frac{\sigma}{\sqrt{n}}$$

$\bar{x} = \text{Sample Mean}$

$Z = \text{Critical value from the standard normal}$

$\sigma = \text{Population Standard Deviation}$

$n = \text{Sample Size}$

The equation below shows that the confidence level is related to the significant level (Appinio Research, 2023).

$$C = 1 - \alpha$$

$C = \text{Confidence Level}$

$\alpha = \text{Significance Level}$

6.Results and Discussion

The results obtained from the experiment were not entirely precise or accurate due to several contributing factors. One primary issue was the extended period since the last calibration of the machine, which likely introduced inaccuracies in the measurements. Additionally, human error played a role, as the lack of prior training on the proper operation of the equipment may have affected the reliability of the results.

Specific challenges were also encountered during the testing of the brake disc. The disc exhibited a poor surface finish and significant rust, both of which impeded the accuracy of the measurements. These surface conditions created additional complications that further impacted the overall quality of the experimental data.

An analysis of the results from the brake disc measurements indicates that the data falls within the near field region. This presents a challenge, as measurements within the near field are affected by the proximity to the crystal, resulting in a non-uniform beam profile. This non-uniformity further reducing the reliability of the results but also imaging on the screen (Laura-Kristin Scholtz, 2016).

The experimental results were further analysed using graphical representations to evaluate the accuracy of the data. One of the key graphs generated was a bell curve, which illustrates the normal distribution of the data. The normal distribution represents how the measurements are distributed around the mean value. The shape of the bell curve provides insight into data variability. A wider curve indicates greater variation and data that is more dispersed from the mean, whereas a steeper curve suggests that the data is closely clustered around the mean.

As shown in Figure 9, the bell curve for the steel block measurements displays a steep peak. This indicates that the data is less spread out and closely centred around the mean, suggesting greater accuracy in these results. In contrast, the bell curve for the brake disc measurements, as shown in Figure 10, has a flatter shape. This indicates that the data is more widely dispersed from the mean, showing greater variability and errors in the measurements. Additionally, confidence levels were incorporated into the graphs to quantify the likelihood that the true value of the measured parameter falls within a specified range (The Editors of Encyclopaedia Britannica, 2024).

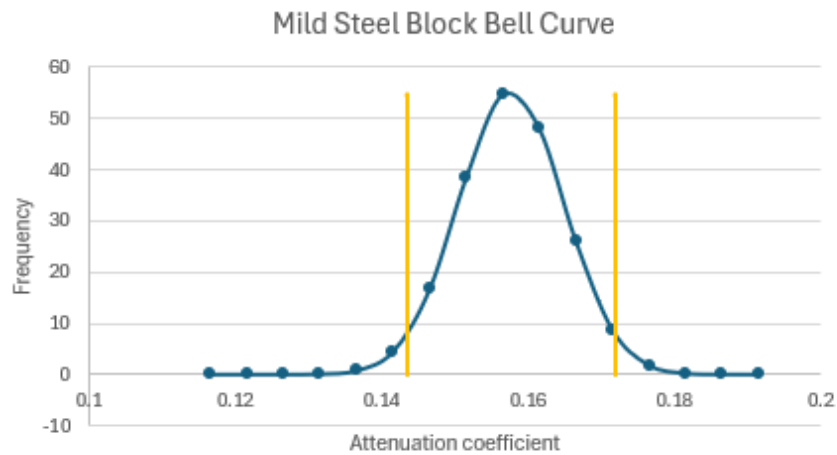
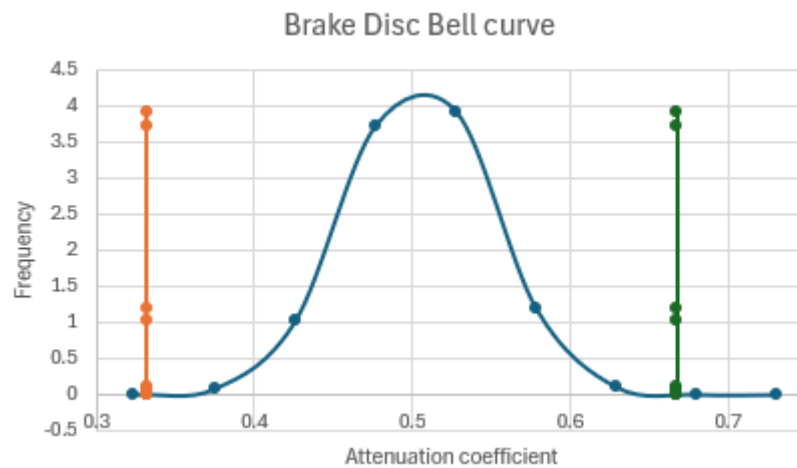


Figure 9: Steel Block Bell Curve



7. Conclusion and bibliography

The experiment was initially done to determine the attenuation coefficient and analyse the data collected from a steel rectangle block and an old brake disc. While the results brought some good insight into the type of testing, they also showed issues from lack of calibration from the machine but also human error, with material imperfections such as rust.

For the steel block, the attenuation coefficient was successfully calculated, and the results demonstrated consistency in certain measurements. However, discrepancies were observed when testing lengthways due to beam spread causing reflections from sidewalls and irregular reflections caused by grain structures. In the case of the brake disc, measurements were further complicated by the material's surface condition and the near-field effect, which reduced the reliability of the data.

The experiment underscores the importance of proper equipment calibration, operator training, and material preparation to minimise errors and enhance the accuracy of ultrasonic testing. Future improvements could include using freshly calibrated equipment, applying standardised training protocols, and preparing the material surfaces to reduce interference.

Despite the limitations, the experiment provided valuable insights into ultrasonic testing methodologies and highlighted areas for refinement in both theory and practice. This information serves as a basis for further studies to optimise testing accuracy and reliability in structural integrity assessments.

Attenuation coefficient	Echo	Attenuation coefficient	Echo2	Attenuation coefficient	Echo3	Mean
0.478411804	1 to 2 hub	0.560157807	2 to 3 hub	0.519284806	1 to 3 hub	0.519285
0.589518951	1 to 2 hub	0.601436161	2 to 3 hub	0.595477556	1 to 3 hub	0.595478
0.481065068	1 to 2 hub	0.485640088	2 to 3 hub	0.483352578	1 to 3 hub	0.483353
0.581191031	1 to 2 hub	0.660568568	2 to 3 hub	0.6208798	1 to 3 hub	0.62088
0.657268451	1 to 2 hub	0.731261944	2 to 3 hub	0.694265197	1 to 3 hub	0.694265
0.494440529	1 to 2 hub	0.512888489	2 to 3 hub	0.503664509	1 to 3 hub	0.503665
0.539814323	1 to 2 hub	0.588829211	2 to 3 hub	0.564321767	1 to 3 hub	0.564322
0.543158917	1 to 2 hub	0.622469385	2 to 3 hub	0.582814151	1 to 3 hub	0.582814
0.490831923	1 to 2 hub	0.507696654	2 to 3 hub	0.499264289	1 to 3 hub	0.499264
0.447041741	1 to 2 hub	0.503117883	2 to 3 hub	0.475079812	1 to 3 hub	0.47508
0.430042851	1 to 2 hub	0.530872957	2 to 3 hub	0.480457904	1 to 3 hub	0.480458
0.323782332	1 to 2 hub	0.453457731	2 to 3 hub	0.388620032	1 to 3 hub	0.38862
0.388940362	1 to 2 hub	0.414335159	2 to 3 hub	0.40163776	1 to 3 hub	0.401638
0.430042851	1 to 2 hub	0.445362659	2 to 3 hub	0.437702755	1 to 3 hub	0.437703
0.63385357	1 to 2 hub	0.681601792	2 to 3 hub	0.657727681	1 to 3 hub	0.657728
0.490800106	1 to 2 hub	0.533686661	2 to 3 hub	0.512243384	1 to 3 hub	0.512243

Figure 11: Brake Disc Attenuation Table

Attenuation coefficient	Echo	Attenuation coefficient	Echo2	Attenuation coefficient	Echo3	Mean
0.15843684	1 to 2 width	0.15843684	2 to 3 width	0.15843684	1 to 3 width	0.11882763
0.164223884	1 to 2 width	0.152649795	2 to 3 width	0.15843684	1 to 3 width	0.11882763
0.160962568	1 to 2 width	0.125389035	2 to 3 width	0.143175801	1 to 3 width	0.10738185
0.166650036	1 to 2 width	0.132134748	2 to 3 width	0.149392392	1 to 3 width	0.11204429
0.167063375	1 to 2 width	0.130864172	2 to 3 width	0.148963773	1 to 3 width	0.11172283
0.14368488	1 to 2 width	0.053398758	2 to 3 width	0.098541819	1 to 3 width	0.07390636
0.155632191	1 to 2 width	0.095484259	2 to 3 width	0.125558225	1 to 3 width	0.09416867
0.15843684	1 to 2 width	0.059970185	2 to 3 width	0.109203513	1 to 3 width	0.08190263
0.152649795	1 to 2 width	0.098466654	2 to 3 width	0.125558225	1 to 3 width	0.09416867
0.149231191	1 to 2 width	0.11476619	2 to 3 width	0.131998691	1 to 3 width	0.09899902

Figure 12: Steel Block Attenuation Table

Figure 12 and Figure 13 both represent how well the material absorbs the waves so the lower the number the less energy the material has absorbed so when comparing the steel block to the brake disc it can be seen that the steel block absorbs a lot less energy and therefore it can penetrate into the material more and find defects deeper (Ono, 2020).

References

- Appinio Research. (2023, December 05). *Appinio*. Retrieved from Appinio: <https://www.appinio.com/en/blog/market-research/statistical-significance>
- Bobbitt, b. Z. (2020, April 21). *Statology*. Retrieved from Statology: <https://www.statology.org/confidence-intervals/>
- hse. (2000, November 01). *www.hse.gov.uk*. Retrieved from hse: <https://www.hse.gov.uk/comah/assets/docs/ndt1.pdf>
- Iowa State University. (2024, December 15). *Iowa State University*. Retrieved from Iowa State University: <https://www.nde-ed.org/NDETechniques/Ultrasonics/EquipmentTrans/beamspread.xhtml>
- Laura-Kristin Scholtz. (2016, January 01). *BayerCollab*. Retrieved from BayernCollab: <https://collab.dvb.bayern/display/TUMzfp/Ultrasonic+Pulse-Echo+Method>
- Ono, K. (2020). A Comprehensive Report on Ultrasonic Attenuation of Engineering Materials, Including Metals, Ceramics, Polymers, Fiber-Reinforced Composites, Wood, and Rocks. *Elastic Waves and Acoustic Emission for Innovative Monitoring of Structures and Engineering Systems*. Retrieved from <https://www.mdpi.com/2076-3417/10/7/2230>
- The Editors of Encyclopaedia Britannica. (2024, December 09). *Britannica*. Retrieved from Britannica: <https://www.britannica.com/topic/normal-distribution>



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Part 2

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<i>Module Number</i>	ACEA7013
<i>Module Name</i>	Structural Integrity & Materials Evaluation
<i>Student Number</i>	2306046
<i>Student Name</i>	Roland Magyar
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Abstract

This technical report discusses the application of ultrasonic testing in the evaluation of defect sizing accuracy for a group of 10 operators. The study of Probability of Detection (PoD) was based on measurements of 21 defects to assess the performance of the operators in terms of bias, coefficient of variation (CV), and confidence intervals. Bias described the average deviation between the measured and true size of the defects, while CV outlined the consistency of the measurements. Confidence intervals were calculated to establish statistical reliability for the calculations and plots. The results showed that the operators' accuracy varied, some tended to overestimate the defect sizes, while others were closer to the true defect sizes. Technicians 3 and 5 were found to be the best operators based on their low bias and CV values, and their performance was further studied using linear regression against the true defect sizes. The paper underlines the importance of systematic assessment in non-destructive testing (NDT), focusing on operator training and consistency in accuracy and reliability.

1.Introduction

This technical report presents the application of ultrasonic testing to determine the accuracy and reliability of defect sizing made by 10 operators. Using data provided from a Probability of Detection (PoD) study, the performance of each operator was assessed based on their measurements of 21 defects. It is intended to determine the most consistent and accurate operators based on bias, coefficient of variation, and confidence intervals using statistical measures. Ultrasonic testing in NDT has been one of the most usable test methods due to its non-destructive nature, enabling the detection and characterisation of flaws within a material. However, this method involves accuracy that may be affected by multiple factors such as operator technique, equipment calibration, and material properties. But this study focuses more on the operator's skill. Calculations were done in MATLAB and Excel, along with visualisation of the results. Bias was used as a measure of average deviation of operators' measurements from the true defect sizes and variability in the measurements using CV. Confidence intervals have been calculated to give a statistical range within which the real values are likely to fall this ensures reliability in the analysis. The insights drawn from this report contribute to understanding the importance of consistent operator training for measurement accuracy.

2.Method/Process

A data set of 10 operator's measurements was given the goal was to determine which operator was the best among the others. Calculations and graphs of this study were done through Microsoft Excel and MATLAB respectively. Equations used to compute for the analysis will be found in the "Equations" section. One of the main calculations done was the R^2 , which is a statistical data representing the proportion of variance in the dependent variable explained by variance in the independent variable (Romeo, 2020). This number will help us understand just how well the measurements of the operators correlated with the true values. The other most important calculation is the computation of the confidence interval. It forms a range of values that can be derived from the sample data, which is expected to contain the true population parameter at a given confidence level. In this study, 95 percent was considered as a confident level that means, if this experiment had been repeated several times (Bobbitt, 2020), then 95% of the calculated intervals would have covered the true population value. This approach provides a robust measure of the reliability of the operators' measurements.

3.Measurements and Graphs of Raw Measurements

Figure 1 shows the raw data from the 10 operators. Each operator was required to identify and measure 21 defects to evaluate the accuracy of the operators in defect sizing. This dataset forms the basis for assessing the performance and reliability of each operator's measurements.

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 13:Operator Table

Data for the following analysis are sourced from a PoD study and plotted against a reference true line. The true line represents the actual size of the defects present in the component, serving as a benchmark for comparison. As the chart in Figure 2 shows the results each operator illustrates that operators have variability around their measurements, where individual data points vary in a range above and below the true line. This depicts the different levels of accuracy and precision for the operators.

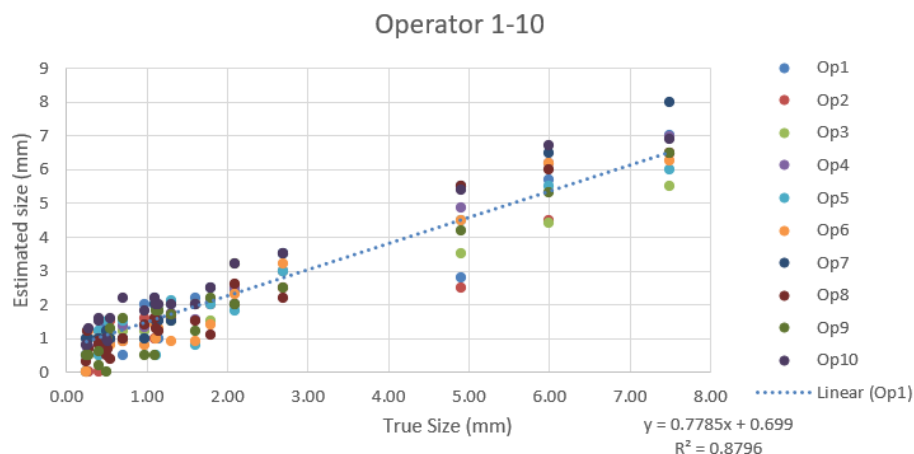


Figure 14: 10 Operator linear regression Graph

4. Calculations and error estimates

The following formula gives the slope of the line, which is a measure of the line's incline. This parameter gives the relationship between the dependent and independent variable it shows how changes from variations in one variable influence the other

$$y = mx + c$$

y = rate of change

m = gradient

c = y intercept of the line

The average was calculated using the equation as shown below, which gives an indication of the central tendency of the dataset, describing the mean value of the observations.

$$\mu = \frac{x_i}{n}$$

μ = The mean (Average)

x_i = Each value in the dataset

n = Total number of values in dataset

The equation for calculating the standard deviation is provided below. This equation is used to determine the degree of variability or dispersion within a dataset, offering insights into the consistency and reliability of the measurements (MathisFun, 2024).

$$\sigma = \sqrt{\frac{\sum_{i=1}^n (x_i - \mu)^2}{n}}$$

σ = Population standard deviation

x_i = Each individual point

μ = Population mean

n = Number of points

The equation below was used to calculate the bias for each operator. The results derived from this equation are presented and further analysed in the Results section, where the concept of bias and its application in evaluating operator performance are explained in detail (PennState, 2024).

$$Bias = \frac{1}{n} \sum_{i=1}^n (x_i - t_i)$$

x_i : The measured value for the i – th observation

t_i : The true value for the i – th observation

n : The total number of observations

Confidence interval equation, shown below, was used for the straight-line graphs to see if the operators estimates would fall in the specified limits (Appinio Research, 2023).

$$Confidence\ Interval = \bar{x} \pm Z \cdot \frac{s}{\sqrt{n}}$$

$\bar{x}$ = Sample mean

Z = Z score corresponding to desired confidence level ($Z = 1.96$ for 95%)

s = Standard deviation

n = Sample size

5.Results and Discussion

Figure 3 presents a bar chart illustrating the coefficient of variation (CV) for each operator, with the CV expressed as a percentage. A lower CV percentage indicates greater accuracy and consistency in the operator's measurements. The bars in the chart are color-coded for clarity: red bars represent operators who were excluded from further analysis due to their high CV values, indicating significant variability in their measurements.

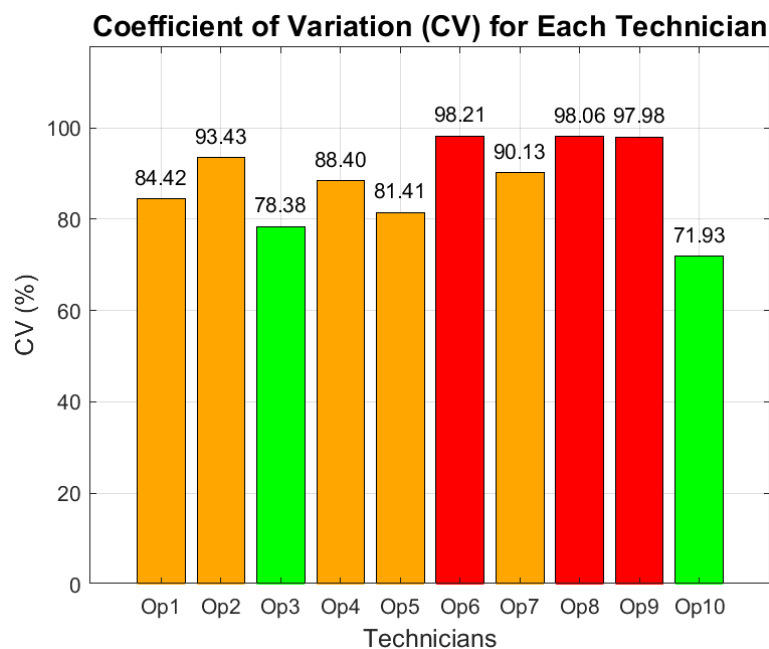


Figure 15: Coefficient of Variation Bar Chart

To identify and narrow down the most accurate operators, the data was analysed, and the bias for each operator was calculated. Bias is defined as the average difference between the measured values and the true defect sizes. A positive bias indicates that the operator is overestimating defect sizes, while a negative bias signifies underestimation. When analysing the bias data, it provides insights into the relationship between the measured defect sizes and their true sizes, rather than the consistency of the measurements themselves. This makes bias a key parameter in assessing the accuracy of each operator.

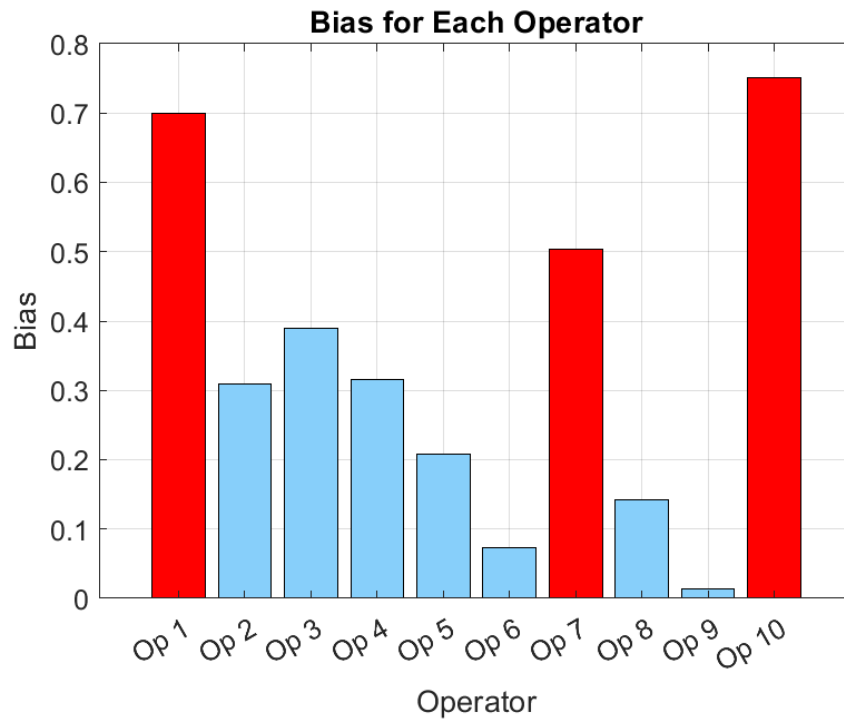


Figure 16: Bias Bar Chart

The bar chart in Figure 4 highlights that Technician 10 exhibits the highest bias, with a value of 0.75, indicating the greatest tendency to overestimate defect sizes. In contrast, Technician 9 demonstrates the lowest bias at 0.013, reflecting measurements that closely align with the true defect sizes. Technicians 6 and 8 show relatively small biases of 0.072 and 0.149, respectively, indicating good accuracy in their measurements when compared to the true defect sizes. The remaining operators exhibit moderate biases, suggesting a level of accuracy that is neither highly precise nor excessively variable.

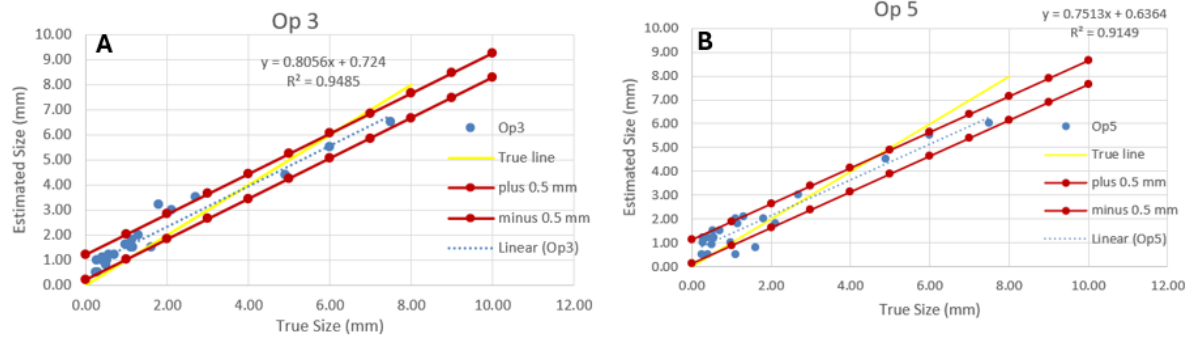


Figure 17: Operator 3(A) Operator 5 (B)

Based on the results from the bias bar chart, Operators 3 and 5 were selected for further comparison. This decision was based on their relatively low bias values and their positions on the lower end of the CV spectrum. Figure 5 shows the linear regression graphs for these two operators, illustrating how closely their measurements aligned with the true defect sizes during the test. Additionally, the graphs include indicators representing a deviation of $\pm 0.5\text{mm}$ from the true size, providing a visual reference for assessing the accuracy of their measurements and highlighting the extent of their deviations.

6. Conclusion and bibliography

The results of this study highlight the effectiveness of ultrasonic testing in evaluating defect sizes, while also emphasizing the variability in operator performance. Using data from 10 operators, key parameters such as bias, coefficient of variation (CV), and confidence intervals were calculated to assess accuracy and consistency. Some key findings were that operator 10 had the lowest CV but that didn't mean he would be the most accurate operator as when bias was used it showed that he was overestimating the size of the defects too much. So therefore, the final analysis, using linear regression, focused on Operators 3 and 5, who displayed moderate bias and acceptable CV values. This approach further narrowed down the most reliable operators based on how closely their measurements aligned with the true defect sizes.

7.References

- Appinio Research. (2023, December 05). *Appinio*. Retrieved from Appinio:
<https://www.appinio.com/en/blog/market-research/statistical-significance>
- Bobbitt, b. Z. (2020, April 21). *Statology*. Retrieved from Statology:
<https://www.statology.org/confidence-intervals/>
- hse. (2000, November 01). *www.hse.gov.uk*. Retrieved from hse:
<https://www.hse.gov.uk/comah/assets/docs/ndt1.pdf>
- MathisFun. (2024, December 01). *Math is Fun*. Retrieved from Math is fun:
https://www.mathsisfun.com/data/standard-deviation-formulas.html?utm_source.com
- PennState. (2024, December 01). *PennSate*. Retrieved from PennState Elderly College of Science: <https://online.stat.psu.edu/stat509/lesson/4/4.3>
- Romeo, G. (2020). Data analysis for business and economics. *Elements of Numerical Mathematical Economics with Excel*, 695-761. Retrieved from
<https://www.sciencedirect.com/topics/mathematics/determination-coefficient>