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Ultrasonic Attenuation Coefficient Determination and Probability of Sizing Analysis

Structural Analysis and Material Evaluation FF005
Part 1: Ultrasonic Attenuation Coefficient Determination

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Abstract

This study utilized ultrasonic testing to evaluate the structural integrity of two specimens: a steel block and a brake disc. The investigation focused on the distinct internal properties of each material, revealing differences in attenuation coefficients and internal scattering characteristics given by the visual statistical results. Analysis of the echo patterns indicated minimal internal flaws in the steel block due to its lower attenuation coefficient. In contrast, the brake disc exhibited greater variability and signs of potential flaws.

Factors such as visible rust on the brake disc were identified as possible contributors to the observed variability. Future work could explore the influence of rust on attenuation coefficients across different materials and its impact on energy loss during flaw detection. Statistical methodologies, including the Shapiro-Wilk test for normality and the D'Agostino test for goodness of fit, are suggested to further analyze and understand the variability and distribution of the data.

1.Apparatus

- **Ultrasonic Flaw Detector:** Silverwing D-Scan 705

The D-SCAN 701 and 705 units are high-performance digital ultrasonic flaw detectors (SILVERWING, n.d.) used for locating internal flaws in materials through wave reflection.

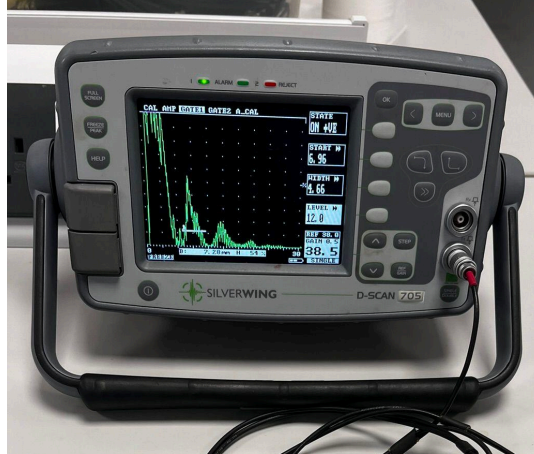


Figure 1. D-SCAN 705

- **Probe:** 5 MHz Transducer

A 5MHz probe was employed to emit and receive the ultrasonic waves for flaw detection.



Figure 2. Prove 5 MHz Transducer

- **Couplant:** Water and Gel

Water and hair gel were used as couplants for effective ultrasonic signal transmission. A couplant is a material (usually liquid) that facilitates the transmission of ultrasonic energy from the transducer into the test specimen (www.nde-ed.org, n.d.).

- **Materials to be Tested:**

Material 1 - Steel Block	Material 2 - Brake Disc
 Figure 3. Brake Disc	 Figure 4. Brake Disc
Material: Steel	Material: Cast Iron Carbon
Thickness: 19 [mm]	Thickness: 7 [mm]
Propagation velocity of materials (C): Steel (Mild) $5.96 \cdot 10^3$ [m/s] [Source]	Propagation velocity of material (C): Cast Iron $3.5 - 5.6 \cdot 10^3$ [m/s] [Source]

Table 1. Table of ultrasonic wave velocity for different materials [Lecture]

Material Units	Velocity (C) m/s $\times 10^3$	Velocity (S) m/s $\times 10^3$	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

2. Introduction

Non-destructive Testing is one part of the function of Quality Control and is complementary to other long-established methods. By definition non-destructive testing of materials, for surface or internal flaws or metallurgical conditions, without interfering in any way with the integrity of the material or its suitability for service. The technique can be applied in production quality control systems. (Willcox, Li and Downes, n.d.). The most common way of doing it is by examination of the component with one or a combination of various Non-Destructive Testing Techniques to determine the presence or absence of flaws in the component. If the flaw exists, then it is characterized with respect to location, size, orientation, shape, nature, etc. to determine its acceptability under the operating conditions (P. P. Nanekar and B. K. Shah, n.d.).

For the past years implementing NDT as part of a predictive maintenance strategy can significantly reduce the likelihood of catastrophic failures. For example, ultrasonic testing has been used extensively in the oil and gas industry to assess the integrity of pipelines and storage tanks, preventing leaks and failures that could have disastrous environmental impacts.

An example of how this procedure is applied can be seen in the case study from Sutro Company, which performs ultrasonic inspection of flare stacks to detect cracks or other hidden internal flaws in the steel structure. Measurements can be taken quickly and easily without the need to access the inside of the structure, demonstrating the efficiency and practicality of ultrasonic testing in detecting flaws in challenging environments. (Denmead, 2020). For better understanding of the concept of Ultrasonic sensor flaw detection please refer to Appendix 1.

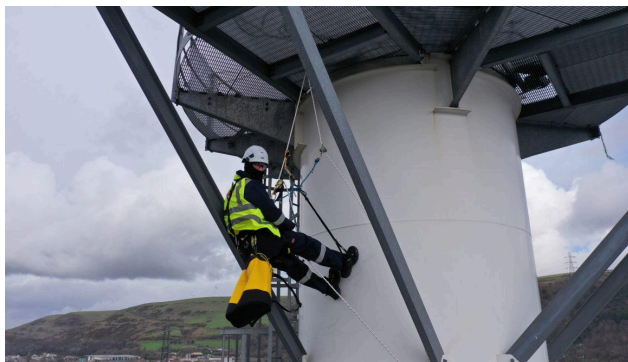


Figure 5. An engineer performing visual and ultrasonic inspection of a Flare Stack (Denmead, 2020)

3. Method - Procedure

This experiment aims to evaluate and compare structural integrity assessment methods using ultrasonic testing to detect flaws in different materials, specifically a steel block and a cast iron-carbon brake disc while incorporating relevant statistical models.

3.1 Equipment Setup

A brief explanation of the apparatus was given to ensure proper handling and avoid damage. The ultrasonic flaw detector and the 5 [MHz] transducer were set up by connecting the probe and power cable to the detector.

3.2 Calibration

When the detector is on, check the velocity, zero, range, and gain for each material. These checks were done individually for the steel block and the brake disc to ensure accuracy when detecting the flaws. In the AMP section of the detector verified that the frequency was set to 5.0 MHz.

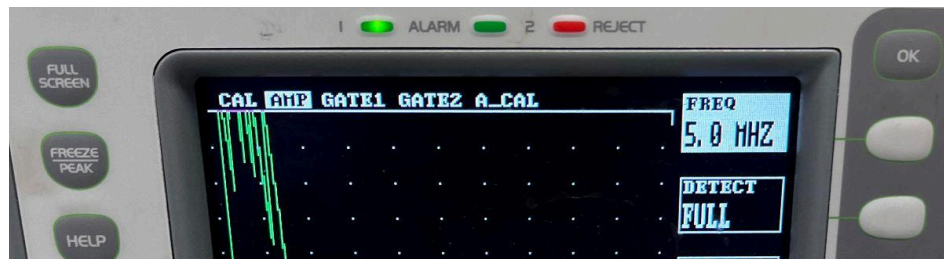


Figure 9. AMP section of the detector.

In Gate 1, ensure that the start, width, level, and reference were appropriate for the amplitude size to accurately detect the peak percentage height of the screen (which represents the amplitude of the wavelength). Adjustments were made to match the unique sound velocity properties of the materials. Even though the velocity values were known, adjustments were made for accurate readings. For the steel block, it was adjusted from 5960 m/s to 5444 m/s, and for the brake disc, the same adjustments were made from 5600 m/s to 5804 m/s.

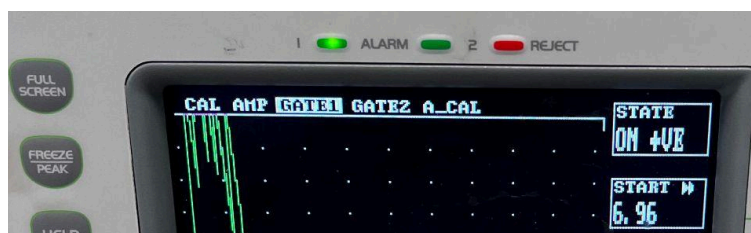


Figure 10. GATE 1 section of the detector.

3.3 Couplant Application

Couplant is applied to the specimens' surface to eliminate air gaps and ensure constant contact between the probe and the material for minimal ultrasonic wave transmission loss.

3.4 Scanning the Steel Block and Brake Disc

The steel block and brake disc were scanned systematically, choosing from a designated area to scan a minimum of 10 points for each piece, and with time 20 data points were collected for the steel block and 10 for the brake disc. To collect the data accurately, the freeze screen option was on every time to ensure no misreadings.

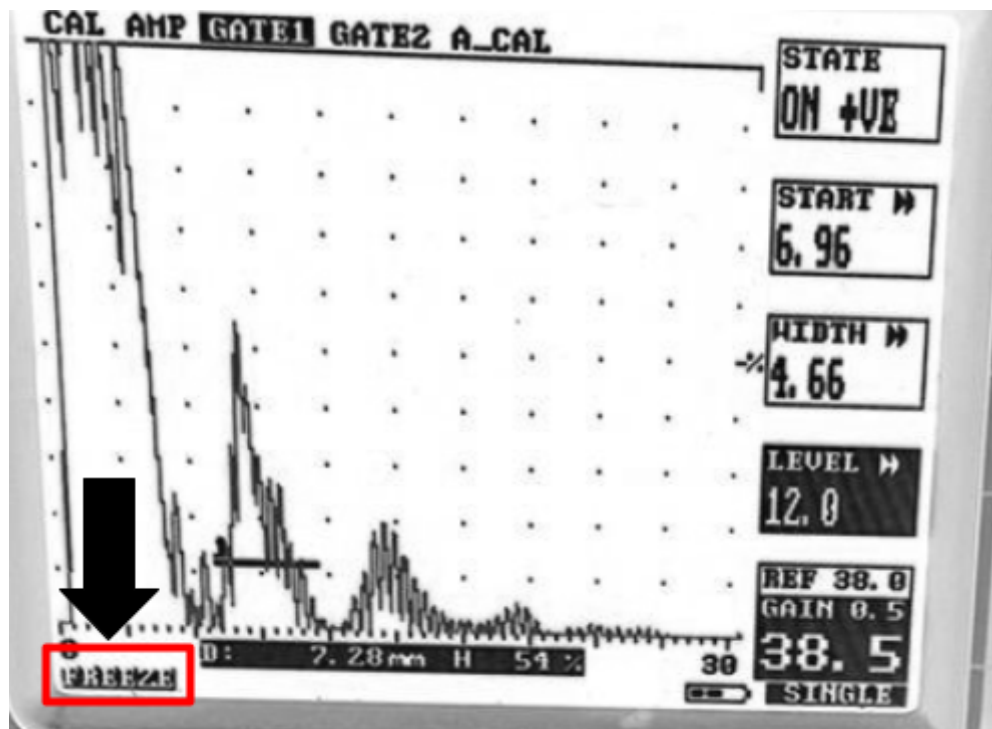


Figure 11. Flaw detector screen

3.5 Cleaning the Workspace

After collecting the data, it was noticeable different echo patterns. With the data collected, proceeded to clean the workspace and put everything back in their respective storage.

4. Measurements and Graphs of Raw Measurements

This section displays the data gathered from the experiment process outlined in the methodology section 3. This is done for the previously mentioned specimens, the steel block and the brake disc. During the ultrasonic testing, raw measurements were collected for both specimens. Different echo patterns were gathered when the ultrasonic waves interacted with the internal structure of the materials hitting the back wall and coming back to the probe.

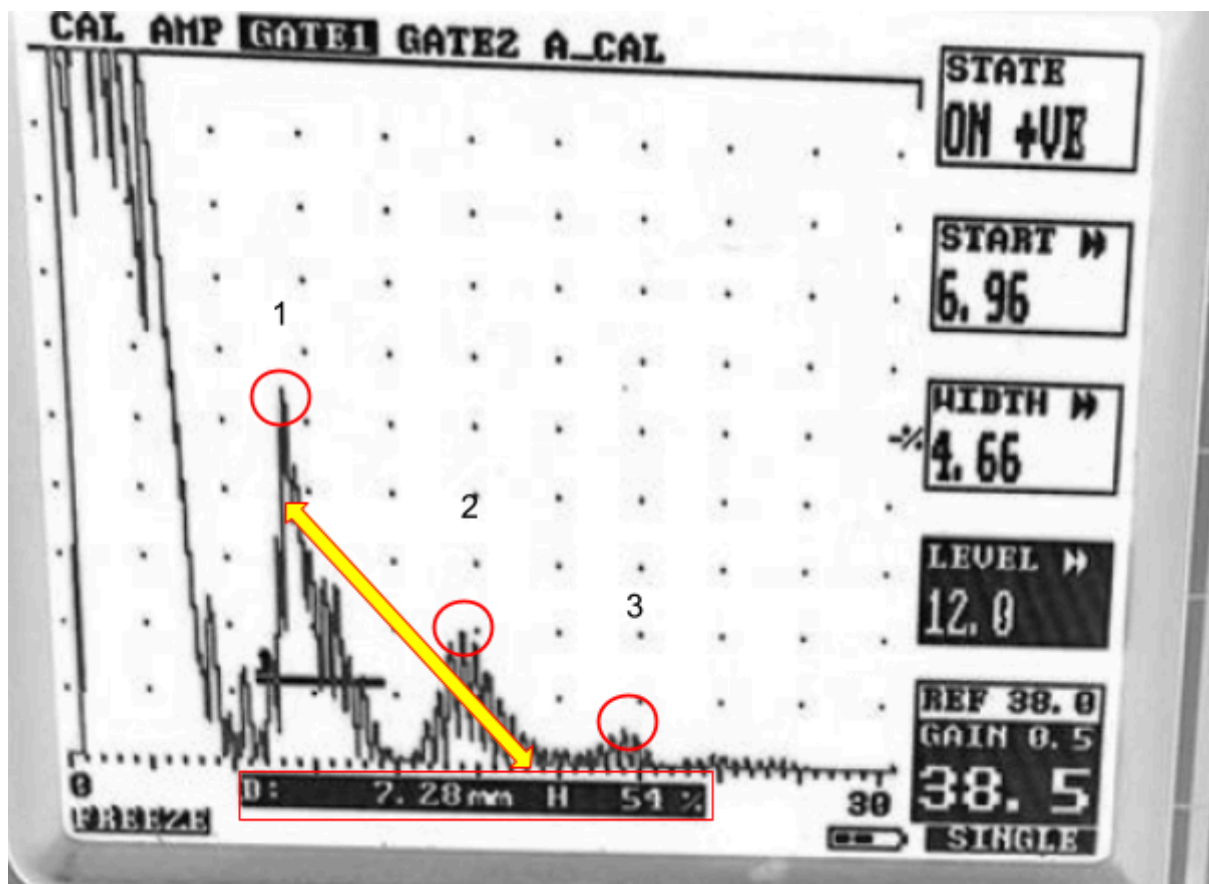


Figure 12. Flaw detector screen

To collect these measurements, first the selected specific locations on the material for flaw inspection. After positioning the ultrasonic transducer, it was ensured a clear view of the echo signals on the detector screen. Once a clear echo was obtained, the image was frozen and measured the section from the initial position to the peak of the wavelength. An example of this can be seen in the Figure above with the red circles, 54% of the full-screen height being the first measurement as the first peak.

4.1 Steel Block

As seen in Figure 12 shows how the data is taken from Echo 1 highlighted in Red 1 (e.g.). The output of the signal amplitude and distance measurements is highlighted in the red square. These results are captured and displayed in Table 2 below.

Table 2. Measurements Taken from the Steel Block

Steel Block						
Measurement	Eco 1	H % of screen	Eco 2	H % of screen	Eco3	H % of screen
1	18,86	90	36,62	43	54,32	21
2	18,9	80	36,4	45	54,32	23
3	19	78	36,4	41	54,32	21
4	19,03	84	36,4	41	54,04	24
5	19,11	85	36,4	49	54,04	30
6	18,86	92	36,4	46	54,32	24
7	18,86	87	36,4	32	54,32	15
8	18,86	91	36,4	41	54,04	19
9	18,86	90	36,4	52	54,04	40
10	18,88	93	36,4	62	54,04	42
Avg 1	18,922	87	36,422	45,2	54,18	25,9
11	18,86	95	36,4	50	54,04	33
12	18,88	94	36,4	46	54,04	25
13	19,03	73	36,4	36	54,32	21
14	19,03	87	36,4	43	54,32	23
15	19,08	76	36,68	39	54,32	25
16	18,86	93	36,4	46	54,04	27
17	18,89	84	36,4	41	54,04	23
18	18,9	79	36,4	39	54,04	21
19	18,76	91	36,4	58	54,04	43
20	19,05	72	36,68	27	54,32	17
Avg 2	18,934	84,4	36,456	42,5	54,152	25,8
Total Avg	18,928	85,7	36,439	43,85	54,166	25,85

Each column represents the percentage height of the screen for different echo positions (Eco 1, Eco 2, Eco 3). The averages (Avg 1, Avg 2, Total Avg) are also calculated to observe the overall behaviour of the echoes.

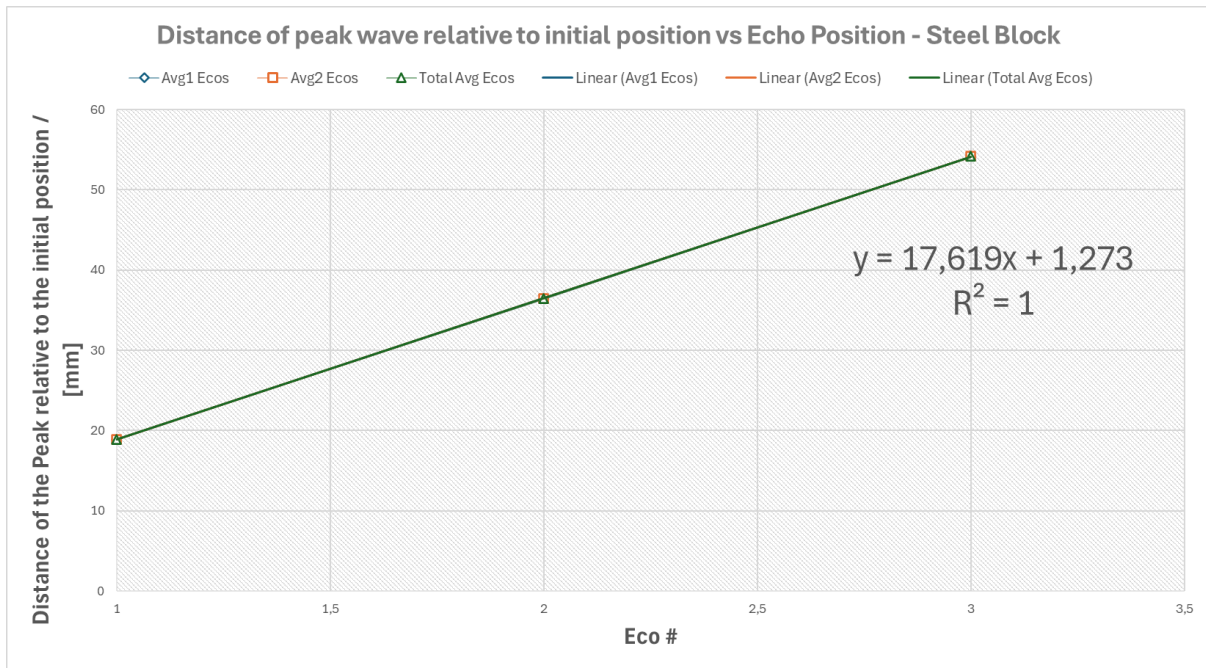


Figure 13. Raw graph with trendlines of the Eco locations for the steel block

In continuation of the data collected and shown in Table 2, Figure 13 displays the trend of displacement increasing with a linear tendency, knowing the thickness of 19 [mm] there is virtually no distortion between the distances (Avg1-2 and Total Avg), it is shown in the graph the trend lines for each eco and the total average are virtually the same. Something to note regarding the graph is that knowing that the thickness is 19 [mm] for the steel block, the Ecos are not reflected in multiples of 19 like 38 and 57 . The equation of the curve should ideally be:

$$y = 19x \quad (1)$$

The equation obtained is:

$$y = 17.619x + 1.273 \quad (2)$$

This discrepancy suggests that there may be minor inaccuracies or factors affecting the readings, and further investigation could help identify the underlying causes.

Figure 13 displays the exponential decrease of the wave amplitude for each echo. As expected, the amplitude decreases as the wave travels back and forth from the initial position through the material. Echo 1 represents the full thickness (19 mm), while Echo 2 and Echo 3 represent subsequent full and partial reflections, respectively. This behaviour is caused by the energy loss when going through the medium.

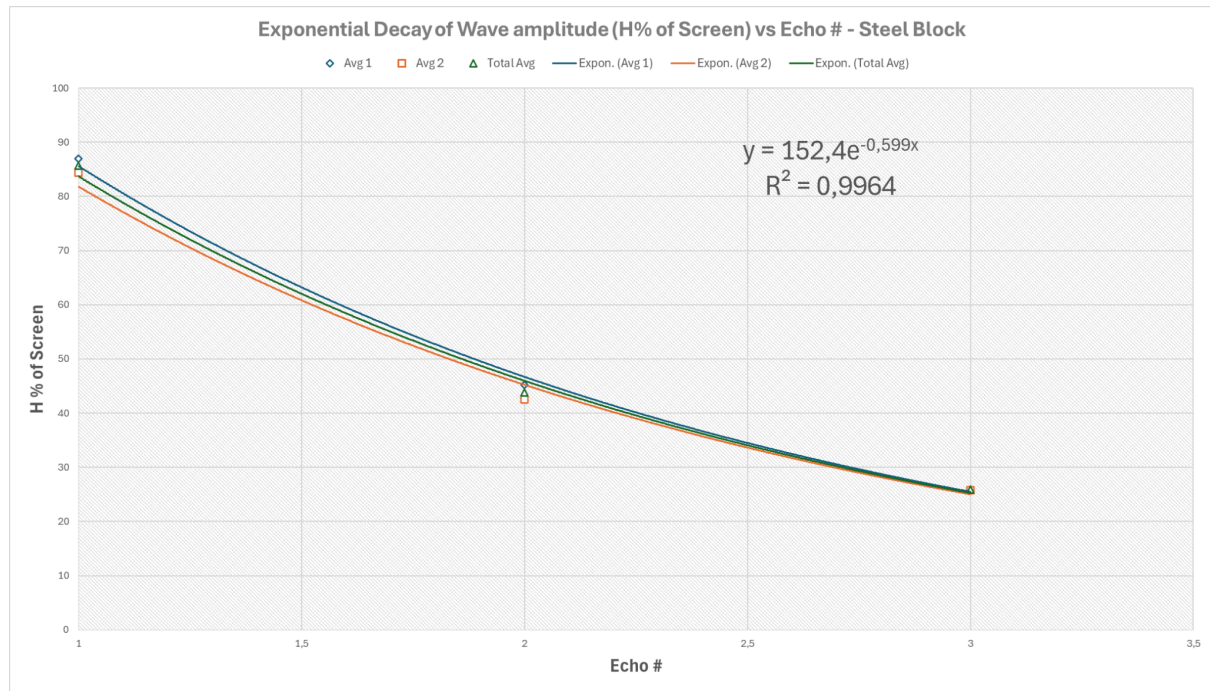


Figure 14. Exponential decay of wave amplitude of Steel Block

The equation for the trendline for the Total Avg is

$$y = 152.4e^{-0.599x} \quad (3)$$

Meaning that the coefficient of the overall decay is $[-0.599]$ for the average values from the table.

4.2 Brake Disc

Similar to the process of the steel block, the measurements for the brake disc were taken and captured in Table 3 below. Only 10 measurements were taken from the specimen.

Table 3. Measurements taken from the Brake Disc

Brake Disc						
Measurement	Eco 1	H % of screen	Eco 2	H % of screen	Eco3	H % of screen
1	7,31	69	13,32	28	19,44	10
2	7,44	80	13,2	40	19,32	18
3	7,56	63	13,56	42	19,92	16
4	7,44	53	13,68	20	19,92	6
5	7,32	62	13,44	24	19,68	9
6	7,32	58	13,32	19	19,56	4
7	7,08	66	12,96	23	18,96	7
8	7,32	70	13,32	30	19,56	9
9	7,56	71	13,32	28	19,56	10
10	7,44	90	14,04	24	20,52	10
Avg 1	7,379	68,2	13,416	27,8	19,644	9,9

The format of the table where data was captured for the steel block and brake disc stayed the same to keep consistency throughout the report. Meaning columns and average values display the same information. With that in mind, the display of the data for the average values of the brake disc is shown in Figure 15. showing a similar behaviour to the steel block, a linear increase in the distance.

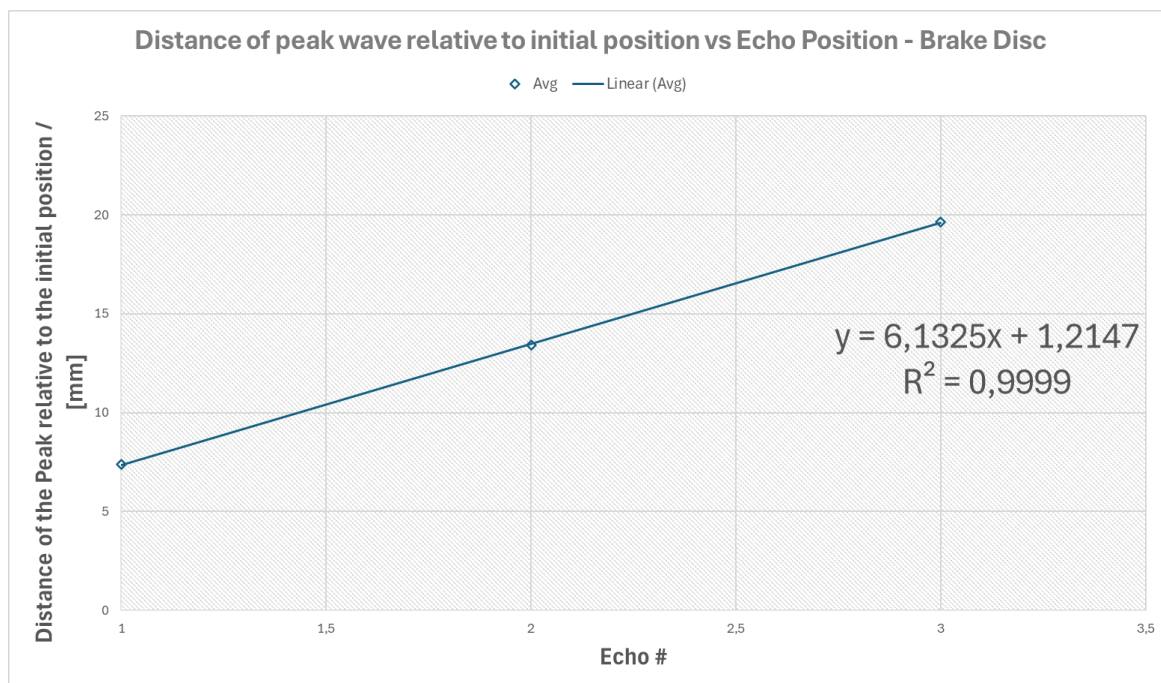


Figure 15. Raw graph with trendlines of the Eco locations for the brake disc

Similar to the case of the steel block it is known that the thickness of the section is 7 [mm] but in each similar it was never 7 [mm] or multiples of 7.

$$y = 7x \quad (4)$$

Instead, the pattern is given by the following linear formula

$$y = 6.1325x + 1.2147 \quad (5)$$

Being close to what is expected is still a positive result but knowing that with the increase in x value, both resulting lines would keep separating more and more is to keep in mind.

Expecting a similar result for the exponential decay of the steel block to the brake disc

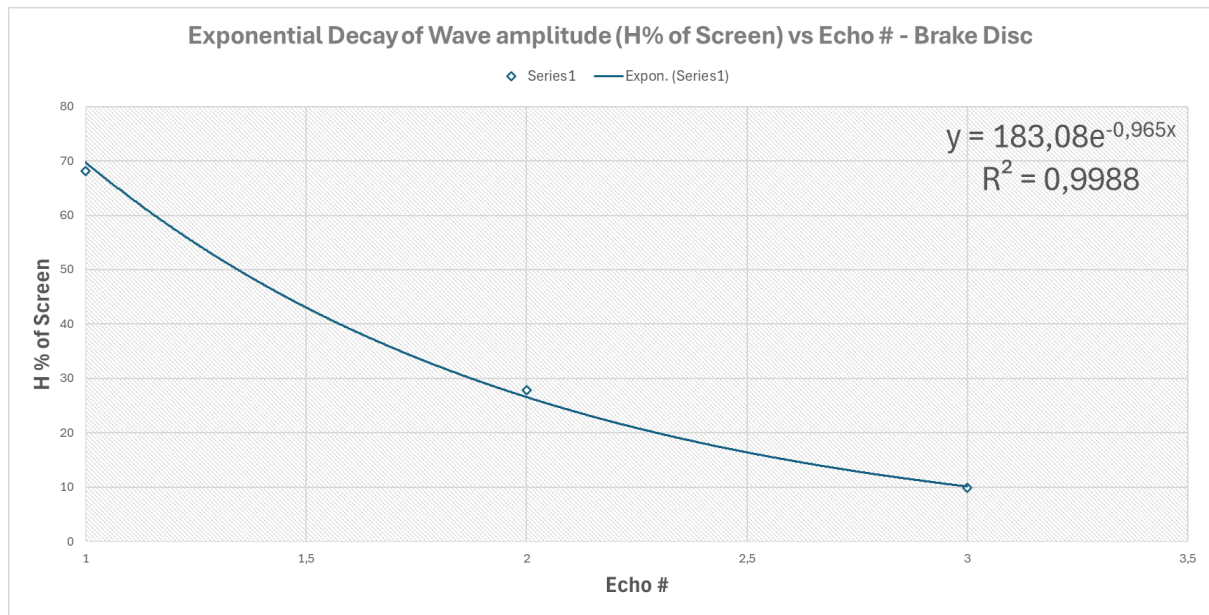


Figure 16. Exponential decay of wave amplitude Brake Disc

The equation for the trendline is

$$y = 183.08e^{-0.965x} \quad (6)$$

Meaning that the coefficient is $[-0.963]$ for the average of the values from the table. In both cases, the steel block and the brake disc, the equation for the attenuation decay is

$$A = A_0 e^{-\alpha z} \quad (7)$$

- A_0 is the amplitude of the propagating wave at some location.
- A is the reduced amplitude after the wave has travelled a distance z from that initial location.
- α is the attenuation coefficient of the wave travelling in the z -direction.
- The term e is Napier's constant which is equal to approximately 2.71828.

5. Calculations and error estimates

5.1 Attenuation Coefficient

With everything and moving to further into the statistical model and using the same equation for the attenuation coefficient rearrange the same equation to find the value of α given the circumstances.

Example of the first value of the steel block taken from the table between Eco 1-2.

$$A = A_0 e^{-\alpha z} \quad (8)$$

$$\frac{A}{A_0} = e^{-\alpha z} \quad (9)$$

$$20 * \log_{10}\left(\frac{A}{A_0}\right) = \alpha z \quad (10)$$

$$\alpha = \frac{20 * \log_{10}\left(\frac{A}{A_0}\right)}{z} \quad (11)$$

Now knowing the equation of the value of alpha use this to our advantage to determine the attenuation coefficient between each Eco and the coefficient per millimetre.

Using the data from the steel block:

$$[A = 43] [A_0 = 90] [Z = 19 \text{ mm}]$$

The attenuation coefficient in the log base:

$$20 * \log\left(\frac{43}{90}\right) = -6.4155 \quad (12)$$

The coefficient of attenuation per millimetre:

$$\alpha = \frac{-6.4155}{(19*2)} \quad (13)$$

$$\alpha = -0.1688 \quad (14)$$

The reason why it multiply the value of $19 * 2$ is due to the total distance travelled by the wave which is two times the thickness, that will only apply from Eco 1-2 and 2-3 but from 1-3 it would require to multiply the thickness by 4 same principle, the distance travelled from Eco 1 to 3 is 4 times the thickness.

5.2 Standard Deviation

To calculate the standard deviation in Excel were used the inbuild function “STDEV.S(Array of Numbers)” but to calculate the value of the standard deviation from a list of numbers is the following. The standard deviation for the values of the steel block will be as follows

Formula of the Sample Standard Deviation (Gilbert-Kawai and Wittenberg, 2014).

$$s = \sqrt{\frac{1}{n-1} \sum_{i=1}^n (x_i - \bar{x})^2} \quad (15)$$

To solve this equation there are a few concepts that need to be specified

- x_i is the value at i position inside the data set
- n is the size of the data set available
- $\sum_{i=1}^n x_i$ is the sum of all values in the data set
- $\bar{x}$ is the mean is the sum of all the data divided by the size n . Also, it is known as the average
- $x - \bar{x}$ is the deviation of a value in comparison to the mean
- S^2 is the variance which measures the dispersion of data from the mean

5.3 The sum of all data values

$$Total\ Sum = \sum_{i=1}^{60} x_i = -8.4693 \quad (16)$$

5.4 Mean

$$\bar{x} = \frac{Total\ Sum}{n} = \frac{-8.4693}{60} \approx -0.141155 \quad (17)$$

5.5 Deviation - Square Deviation

For each data value x_i , calculate

$$Deviation = x_i - \bar{x} \quad (18)$$

$$Squared\ Deviation = (x_i - \bar{x})^2 \quad (19)$$

Calculations for the first 2 values of the square deviation

$$x_1 = -0.1688 \quad (20)$$

$$Deviation = -0.1688 - (-0.141155) = -0.027645 \quad (21)$$

$$Squared\ Deviation = (-0.027645)^2 = 0.000764 \quad (22)$$

$$x_2 = -0.1315 \quad (23)$$

$$Deviation = -0.1315 - (-0.141155) = 0.009655 \quad (24)$$

$$Squared Deviation = (-0.009655)^2 = 0.000093 \quad (25)$$

Continue this calculation for all 60 data points and add them to further obtain the variance

$$Sum\ of\ Squared\ Deviations = \sum_{i=1}^{60} (x_i - \bar{x})^2 = S \quad (26)$$

$$S \approx 0.07539 \quad (27)$$

5.6 The variance

$$s^2 = \frac{S}{n-1} = \frac{0.07539}{59} \approx 0.001278 \quad (28)$$

5.7 Sample Standard Deviation

$$s = \sqrt{s^2} = \sqrt{0.001278} \approx 0.03575 \quad (29)$$

5.8 Percentage Error

The percentage error between this value and the value given by the inbuild function of Excel is

$$Percentage\ Difference = \left(\frac{My\ value - Excel\ Value}{Excel\ Value} \right) * 100 \quad (30)$$

$$Percentage\ Error = \left(\frac{0.03575 - 0.03332193}{0.03332193} \right) * 100 \quad (31)$$

$$Percentage\ Error = 7.28\% \quad (32)$$

There is an important factor to take into account between theoretical value and the Excel value and that is that Excel uses optimized algorithms that handle floating-point arithmetic more precisely. But as the values do not differ too much appropriate to use the inbuild function from Excel to proceed.

5.9 95% Confidence

For confidence levels of 90%, 95% and 99% the z value is 1.65, 1.96 and 2.58, respectively. The standard error depends on the sample size and the dispersion in the variable of interest.

Table 4. Critical (z) values used in the calculation of confidence intervals (Hazra, 2017).

Confidence level	Critical (z) value to be used in confidence interval calculation
50%	0.67449
75%	1.15035
90%	1.64485
95%	1.95996
97%	2.17009
99%	2.57583
99.9%	3.29053

Following this to calculate the upper and lower confidence level, multiply the value of the mean times 1.96, taking away and adding that number creating lower and upper bounds. This is an example of how to calculate it for the steel block and the brake disc would be the same procedure.

$$CI = \bar{x} \pm \bar{x} * z \quad (33)$$

$$CI = 0.141158368 \pm 0.141158368 * 1.96 \quad (34)$$

$$Upper Level = 0.206469347 \quad (35)$$

$$Lower Level = 0.075847389 \quad (36)$$

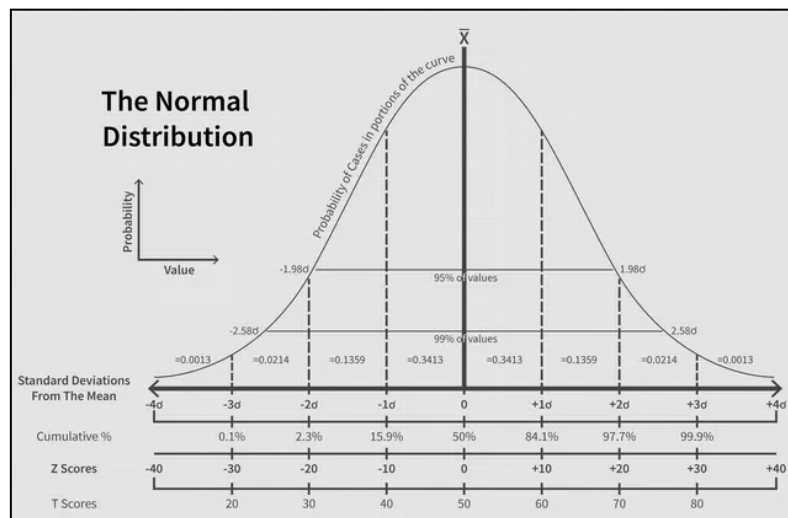


Figure 17. Confidence Intervals (HAYES, 2021)

Having these values and plotting them in the normal distribution graph and get the percentage values that are inside the confidence bounds.

$$\frac{26}{30} * 100 = 87\% \quad (37)$$

There are 26 values inside the bounds over the 30 total values which give us 87% of the total values inside the bounds.

6. Results and Discussion

6.1 Steel Block

The steel block showed consistent echo patterns, indicating a uniform internal structure. Attenuation coefficients showed minimal variability.

Table 5. Attenuation Coefficient data from the Steel Block for each Eco.

Measurement		Eco 1-2		Eco 2-3		Eco 1-3	
		Coefficient - Log	Coefficient/mm	Coefficient - Log	Coefficient/mm	Coefficient - Log	Coefficient/mm
Taken from the rectangle face of the block	1	-6,4155	-0,1688	-6,2250	-0,1638	-12,6405	-0,1663
	2	-4,9975	-0,1315	-5,8297	-0,1534	-10,8272	-0,1425
	3	-5,5862	-0,1470	-5,8113	-0,1529	-11,3975	-0,1500
	4	-6,2299	-0,1639	-4,6515	-0,1224	-10,8814	-0,1432
	5	-4,7845	-0,1259	-4,2615	-0,1121	-9,0460	-0,1190
	6	-6,0206	-0,1584	-5,6509	-0,1487	-11,6715	-0,1536
	7	-8,6874	-0,2286	-6,5812	-0,1732	-15,2686	-0,2009
	8	-6,9252	-0,1822	-6,6806	-0,1758	-13,6058	-0,1790
	9	-4,7648	-0,1254	-2,2789	-0,0600	-7,0437	-0,0927
	10	-3,5218	-0,0927	-3,3828	-0,0890	-6,9047	-0,0909
	11	-5,5751	-0,1467	-3,6091	-0,0950	-9,1842	-0,1208
	12	-6,2074	-0,1634	-5,2964	-0,1394	-11,5038	-0,1514
	13	-6,1404	-0,1616	-4,6817	-0,1232	-10,8221	-0,1424
	14	-6,1210	-0,1611	-5,4348	-0,1430	-11,5558	-0,1521
	15	-5,7950	-0,1525	-3,8625	-0,1016	-9,6575	-0,1271
	16	-6,1145	-0,1609	-4,6279	-0,1218	-10,7424	-0,1413
	17	-6,2299	-0,1639	-5,0211	-0,1321	-11,2510	-0,1480
	18	-6,1312	-0,1613	-5,3769	-0,1415	-11,5082	-0,1514
	19	-3,9123	-0,1030	-2,5992	-0,0684	-6,5115	-0,0857
	20	-8,5194	-0,2242	-4,0183	-0,1057	-12,5377	-0,1650

Attenuation coefficients showed minimal variability, which is present in Table 6. This consistency suggests a low level of internal flaws.

Table 6. Statistical Values required to generate the 95% bounds of the normal distribution.

Mean	-0,141158368
Standard Deviation	0,033321928
95%	0,065310979
minus	0,075847389
Mean	0,141158368
plus	0,206469347

Knowing a low standard deviation means that the values tend to be closer data points to the mean (or expected value).

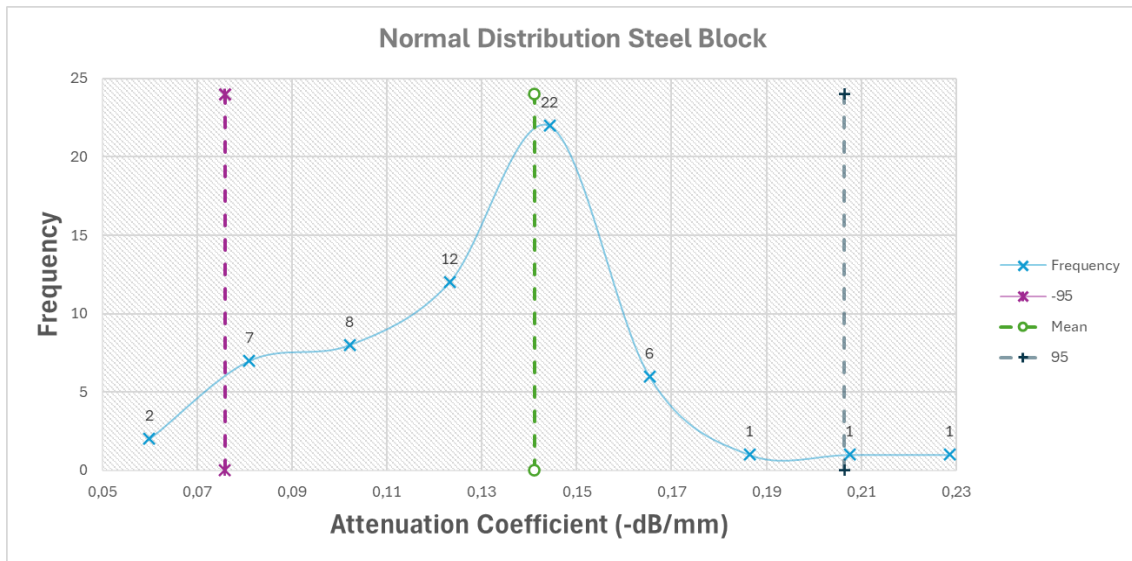


Figure 18. Normal Distribution for the Steel Block - Bell Curve

The normal distribution of the steel block attenuation coefficients shows that most values fall within a narrow range and are towards the lower bound. This indicates that the attenuation is generally low or also fewer defects and better uniform material. The graph was divided into three pieces showing the mean and the 95% boundaries for the distribution.

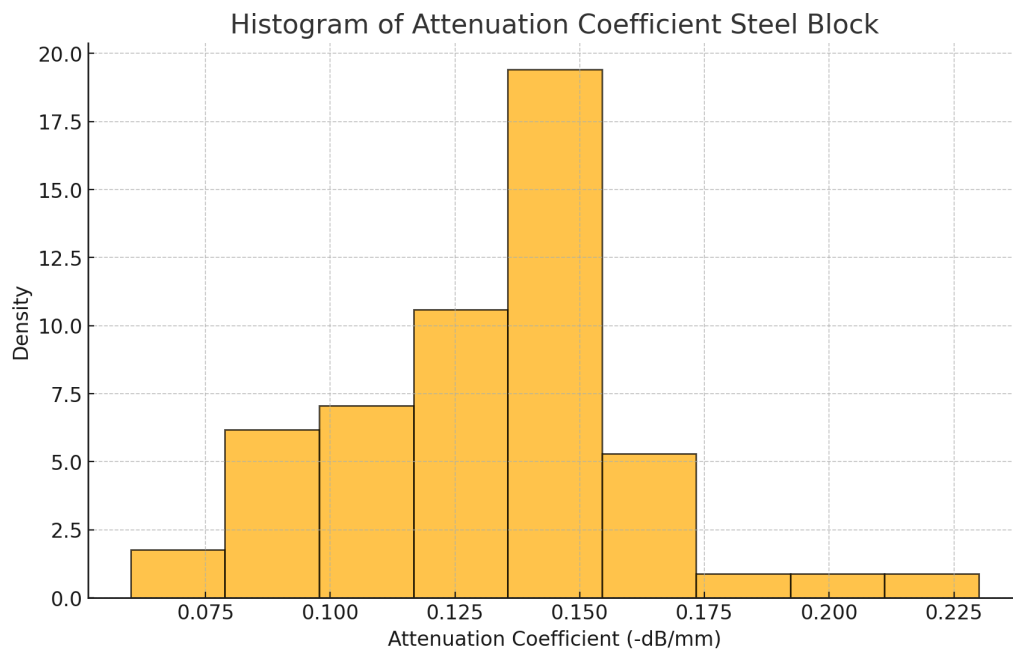


Figure 19. Histogram of Attenuation Coefficient Data for the Steel Block

Visually the data shown in the histogram looks like a half curve of the normal distribution curve that is why it is important to choose wisely the type of graph it to graph the data, because in the bell curve distribution, it looks like a normal distribution curve, but as the data goes further for the range, the frequency/density decreases drastically.

6.2 Brake Disc

Following the same procedure for the steel block, the creation of the table of attenuation coefficients for the brake discs is kept.

Table 7. Attenuation Coefficient data from the Steel Block for each Eco.

Measurement		Eco 1-2		Eco 2-3		Eco 1-3	
		Coefficient - Log	Coefficient/mm	Coefficient - Log	Coefficient/mm	Coefficient - Log	Coefficient/mm
Taken from the rectangle face of the block	1	-7,8338	-0,5596	-8,9432	-0,6388	-16,7770	-0,5992
	2	-6,0206	-0,4300	-6,9357	-0,4954	-12,9563	-0,4627
	3	-3,5218	-0,2516	-8,3826	-0,5988	-11,9044	-0,4252
	4	-8,4649	-0,6046	-10,4576	-0,7470	-18,9225	-0,6758
	5	-8,2436	-0,5888	-8,5194	-0,6085	-16,7630	-0,5987
	6	-9,6935	-0,6924	-13,5339	-0,9667	-23,2274	-0,8295
	7	-9,1563	-0,6540	-10,3326	-0,7380	-19,4889	-0,6960
	8	-7,3595	-0,5257	-10,4576	-0,7470	-17,8171	-0,6363
	9	-8,0820	-0,5773	-8,9432	-0,6388	-17,0252	-0,6080
	10	-11,4806	-0,8200	-7,6042	-0,5432	-19,0849	-0,6816

The attenuation coefficients for the brake disc are greater compared to those of the steel block, indicating that the wave amplitude per echo decreases more rapidly in the brake disc. This is indicative of increased internal scattering and energy loss, likely due to the complex internal structure or visible rust. The statistical values for the 95% bounds of the normal distribution are given in Table 8, indicating a broader range compared to the steel block.

Table 8. Statistical Values required to generate the 95% bounds of the normal distribution.

Mean	-0,621309373
Standard Deviation	0,136895723
95%	0,268315616
minus	0,352993757
Mean	0,621309373
plus	0,889624989

Then from here, it was used the inbuild function of Frequency to create the same graph for the normal distribution of values for the brake disc having a similar pattern to the one from the steel block, noting that the normal distribution of these values are from a smaller set of data.

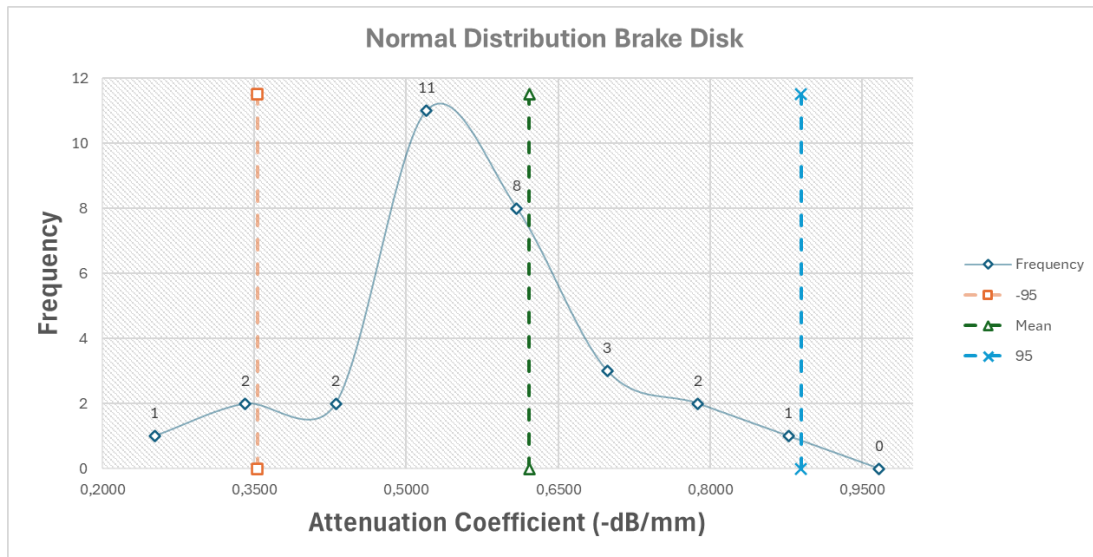


Figure 20. Normal Distribution for the Brake Disk

The normal distribution of the steel block attenuation coefficients shows that most values fall within a narrow range and are towards the middle bound which differs from the data of the steel block. The graph was divided into three pieces showing the mean and the 95% boundaries for the distribution similar to what it was done for the steel block.

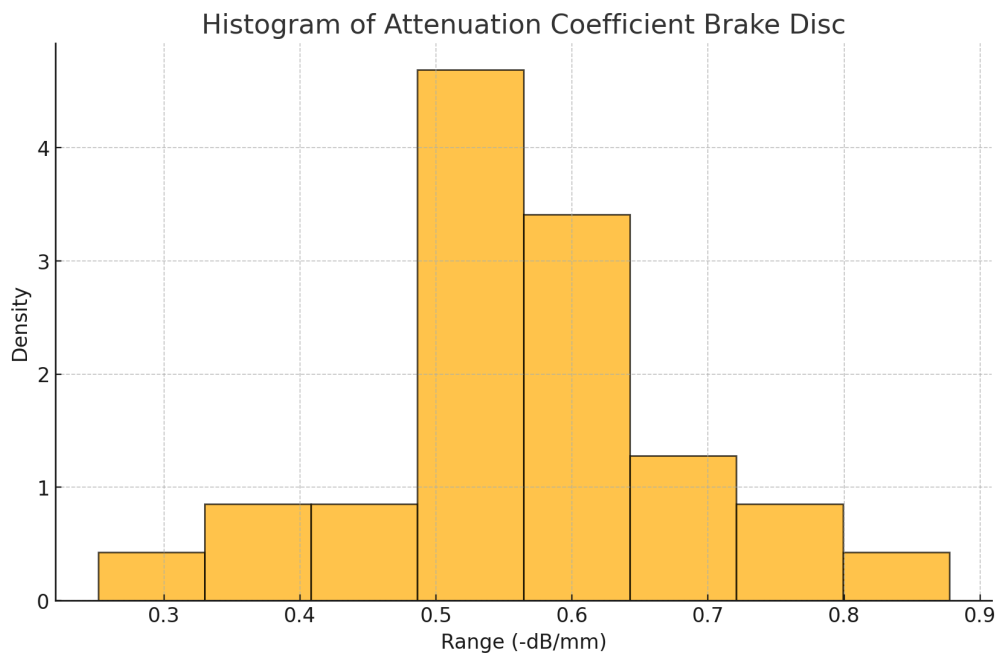


Figure 21. Histogram of Attenuation Coefficient Data for the Steel Block

Visualizing the pattern of the histogram resembles the normal distribution curve, where most data is concentrated in the middle (around 0.5), with fewer data points towards the tail.

7. Conclusion

The experiment employed ultrasonic testing to evaluate the structural integrity of two specimens: a steel block and a brake disc. These specimens were selected for their distinct properties, both visually and internally. Through the testing process, it was confirmed that each material possesses its own unique attenuation coefficient and variability. These differences suggest distinct internal scattering characteristics and potential flaws within the materials.

Analysis of the echo patterns in the steel block revealed minimal internal flaws, attributed to its lower attenuation coefficient. In contrast, the brake disc exhibited greater variability in its echo data, indicating a higher level of internal scattering and potential flaws.

Further investigation could focus on the factors contributing to the variability observed in the brake disc, such as the impact of visible rust on its attenuation coefficient. Questions arise, such as whether rust affects all materials similarly and whether there is a measurable pattern in how it influences energy loss within the material, particularly when detecting flaws.

To deepen the analysis, statistical methodologies could be employed, including tests like the Shapiro-Wilk test and D'Agostino test. The Shapiro-Wilk test statistic (Calc W) measures how well the ordered standardized sample quantiles fit the standard normal quantiles and evaluates the normality of the data distribution (King and Eckersley, 2019), while the D'Agostino test assesses goodness of fit and measures deviations from normality (Das and Imon, 2016). These tools could provide valuable insights into the underlying patterns and variability in the data.

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Appendix: Deeper Understanding for Ultrasonic Flaw Detection

The principle is in some respects similar to echo sounding. A short pulse of ultrasound is generated through an electric charge applied to a piezoelectric crystal, which vibrates for a very short period at a frequency related to the thickness of the crystal. In flaw detection, this frequency is usually in the range of one million to six million times per second (1 MHz to 6 MHz). Vibrations or sound waves at this frequency can travel a considerable distance in material, such as many metals with little attenuation. The velocity at which these waves propagate is related to Young's Modulus for the material and is characteristic of that material (Willcox, Li and Downes, n.d.).

Ultrasonic waves transmitted from a transducer propagate only in the limited region in the form of a beam (this is called an ultrasonic beam) within which material particles vibrate. This is similar to the light from a headlight of an automobile at night.

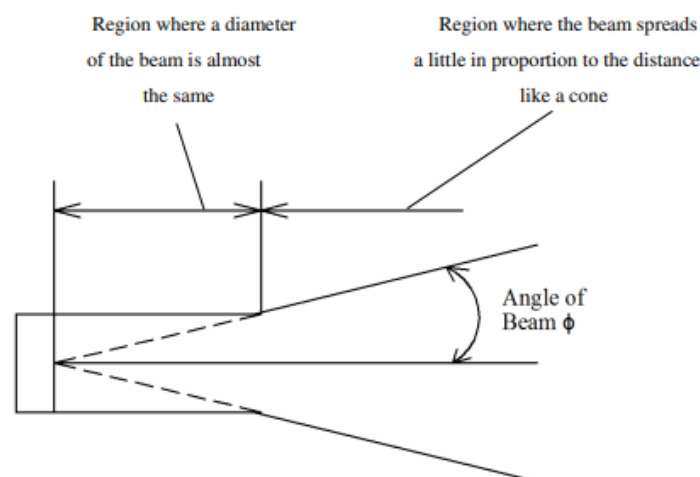


Figure 6. Features of propagation of ultrasonic waves (Gessesew, 2007).

The diameter of the beam is almost the same as far as the distance from a probe (this range is called near field). At a farther distance, the beam spreads a little in proportion to the distance (this is called path length) like a cone as shown in the previous Figure (Gessesew, 2007).

This concept can be taken further by understanding Snell's Law which determines the directions of the reflected and refracted waves when passing from 1 medium to another with different characteristics. According to the research (Training Guidelines in Non-destructive Testing Techniques Manual for Ultrasonic Testing at Level 2 V I E N N A , 2 0 1 8, n.d.) this law is the ratio of the sine of the angle of incidence to the sine of the angle of reflection or refraction equals to the ration of the corresponding velocities of the incident, and reflected or refracted waves.

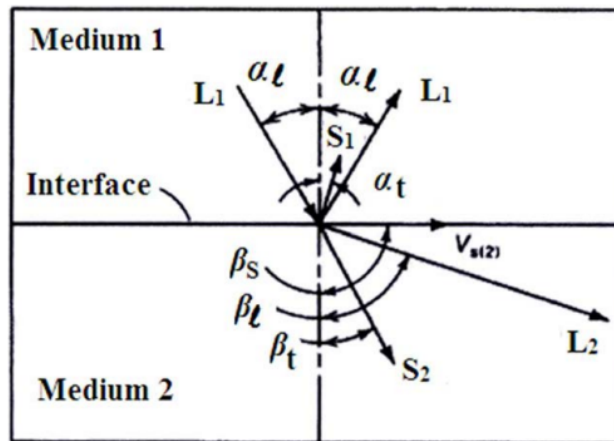


Figure 7. Refraction and mode conversion for an incident longitudinal wave (Training Guidelines in Non-destructive Testing Techniques)

Following this acoustic impedance is important in the determination of acoustic transmission and reflection at the boundary of two materials having different acoustic impedances. The characteristics of the field impedance are defined (Hiremath et al., 2021):

$$Z = \rho * c$$

With the density of the material being ρ and the speed of sound of the same material being c .

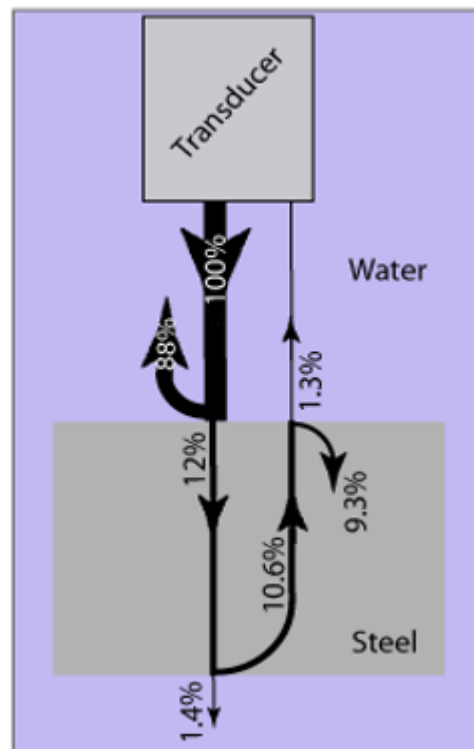


Figure 8. Showcasing the effect of acoustic impedance through two mediums steel and water.

In the case of this experiment, there is only one medium that is going to be working but as expected there is energy loss while passing through the material.

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Ultrasonic Attenuation Coefficient Determination and Probability of Sizing Analysis

Structural Analysis and Material Evaluation FF005
Part 2: Through Wall Sizing Accuracy Analysis

Diego Alexander Valencia Flores
2405760
December 2024

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Abstract

This study aimed to identify the most accurate and reliable technician for ultrasonic flaw detection measurements through a detailed statistical approach. Data from ten operators assessing through-wall thickness were evaluated on multiple criteria: flaw detection capability, absolute and relative errors, linear regression consistency, and adherence to 95% confidence intervals. Operators who missed flaws were removed first, ensuring only those capable of consistently identifying defects remained.

Additional filtering based on error magnitudes, gradient values (relative to the ideal $y=x$ line), and the proportion of data within 95% confidence bounds narrowed the field further. While several operators showed acceptable performance, one technician (Operator 1) stood out, consistently outperforming the others. In contrast, anomalies in Operator 7's measurements—such as an unusually high number of identical values—reinforced the decision that Operator 1 was the best choice. These findings highlight the value of a multi-criteria statistical evaluation for identifying the most dependable technician in critical structural assessments.

Introduction

Key performance indicators (KPIs) are quantifiable measurements used to gauge a company's overall long-term performance. KPIs specifically help determine a company's strategic, financial, and operational achievements, especially compared to those of other businesses within the same sector. They can also be used to judge progress or achievements against a set of benchmarks or past performance (Twin). In different scenarios, it is taken from the macro perspective to the micro perspective analyzing performance for small teams or even of a single person. Determining the different criteria for people's performance can be a bit daunting but at the same time if you don't measure it you won't improve it.

These KPIs can be measured and tracked through analytics software and reporting tools at both scales mentioned. Most KPIs fall into four broad categories. Each category has its characteristics, time frame, and level of business that is likely to use it. In this scenario, it is presented 10 individual operators which can be seen also seen as a whole department if required.

Background

Accurate ultrasonic thickness gauging is critical in evaluating the structural integrity and safety of various components, particularly those susceptible to corrosion or material degradation. Throughout the years, NDT processes have been used to determine the flaws at early stages for different materials. According to (Willcox, Li and Downes, n.d.) Non-destructive Testing is one part of the function of Quality Control and is complementary to other long-established methods. By definition non-destructive testing of materials, for surface or internal flaws or metallurgical conditions, without interfering in any way with the integrity of the material or its suitability for service. But taking a step further is to measure how accurate is not only a certain method but also the methodology and the results perceived.

For this investigation, an Excel spreadsheet with measurements of through-wall thickness was undertaken as part of a larger PoD study used to assess the performance of a new ultrasonic thickness gauging procedure. In total, 21 defect measurements were identified as part of the study, the dimensions of which are given in mm to decimal places for 10 individual technicians. See Table 1 below.

Table 1. Spreadsheet of the true size of a flaw vs the estimate of that same flaw by a technician

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

The approach to determine the sizing accuracy of the individual technicians will be done through linear regression and statistical analysis techniques but taking further the sizing accuracy of each technician at the end will be a table specifying which operator would be the best according to different criteria and the best overall.

Methodology

To determine the overall best operator, multiple performance factors must be considered. In addition to evaluating the basics of Error and Absolute Error, the paper expands the analysis to gather a range of indicators that together offer a more holistic assessment of each operator's accuracy and reliability.

Key Performance Indicators:

1. Error
2. Absolute Error
3. Missed flaws
4. Consistency
5. Offset
6. Under/Oversizing

By examining each of these factors through appropriate statistical and analytical methods, preliminary rankings will be given for each category. These preliminary results, considered both individually and collectively, serve as the foundation for determining which operator performs best overall. All cases will be done for the first operator for the first or necessary calculation as for the other operators will be the same.

These systematic calculations will be done using MATLAB a programming and numeric computing platform used by millions of engineers and scientists to analyze data, develop algorithms, and create models (MathWorks). The final MATLAB will be shared in the appendix as a reference, knowing that for it to work the user needs to import the data spreadsheet by going HOME>Import Data>Select your file>Import Selection. By doing this a new variable (a table) will be created in the workspace section.

Error

For the error, it will be calculated by just having the true size of the flaw minus the value that the operator measures for that same flaw.

$$Error = true\ size - Size\ by\ operator \quad (1)$$

$$Error_1 = 0.25 - 1.00 \quad (2)$$

$$Error = -0.75 \quad (3)$$

The negative value represents that the value presented by the operator was higher than the actual value and contrary if the value had been positive the operator's value would have been lower than the actual value.

As closer the value gets to zero in either direction it means that the operator is more accurate at sizing the value of the defect. This effect can be shown in figure 1 below.

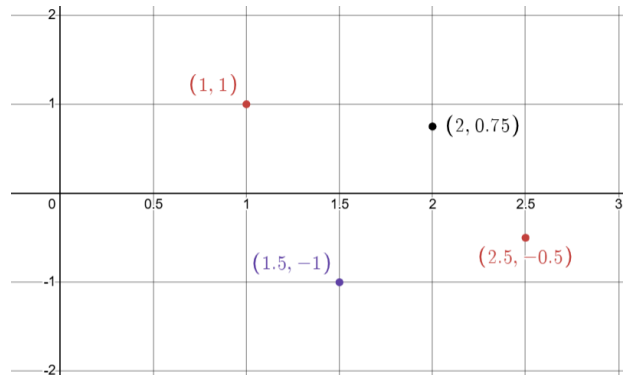


Figure 1. Representation of proximity to zero represents accuracy

Now that is the value for the first error for the first operator. Extrapolating this process and applying it to the defects and all operators, then determining an average of those values it would determine the average error per operator.

$$Sum\ of\ all\ error\ for\ the\ first\ operator = \sum_{i=1}^{21} (Error) = -14.68 \quad (4)$$

$$Average = \frac{\sum_{i=1}^{21} (Error)}{21} = -0.6990 \quad (5)$$

Having the average error for the first operator, it is possible to do this process systematically as mentioned previously for all the operators these results are shown in the table 2 below.

By automating calculations with MATLAB's scripting capabilities instead of relying on manual Excel operations, all operators could be analyzed simultaneously using a simple for-loop giving a preliminary rank to determine which operator performed better at this stage.

Table 2. Operators ranked by Average Error

Operator	AvgError
{ 'Op10' }	-0.75143
{ 'Op1' }	-0.69905
{ 'Op7' }	-0.50381
{ 'Op2' }	-0.40444
{ 'Op3' }	-0.38952
{ 'Op4' }	-0.31462
{ 'Op5' }	-0.20857
{ 'Op8' }	-0.1419
{ 'Op6' }	-0.089
{ 'Op9' }	-0.039

As displayed in table 2 it can be seen that every operator has a different error given the flaw sizes for each flaw. The best operator at this stage is Operator 9 marked with a red box with a -0.039 value close to zero.

Absolute Error

Moving to the absolute error, this error is the positive value of a number. In this case, the absolute value (or modulus) $|x|$ of a real number x is the non-negative value of x without regard to its sign. For example, the absolute value of 5 is 5, and the absolute value of -5 is also 5. The absolute value of a number may be thought of as its distance from zero along a real number line (Wright). For example, taking into account the same average value of the first operator.

$$\text{Operator 1} = -0.6990 \quad (6)$$

Absolute value of this would be the following taking Operator 1 as x .

$$|x| = |-0.6990| \quad (7)$$

$$|x| = 0.6990 \quad (8)$$

Being positive 4 the final answer or the absolute value of x . Following this idea, by making all the errors for each technician positive it is possible to create a new table ranking each operator as shown in table 3 below.

Table 3. Operators ranked by average absolute error

Operator	AvgAbsError
{ 'Op4' }	0.37033
{ 'Op8' }	0.37524
{ 'Op6' }	0.434
{ 'Op9' }	0.477
{ 'Op7' }	0.51333
{ 'Op2' }	0.52111
{ 'Op3' }	0.58952
{ 'Op5' }	0.60095
{ 'Op1' }	0.71524
{ 'Op10' }	0.80857

It is apparent from Table 3 of absolute errors and Table 2 of errors that the Operator rankings differ. This change arises because each operator shows varying consistency in sizing flaws.

Some technicians measure flaws larger or smaller than their actual dimensions, resulting in both positive and negative deviations. By using absolute values to diminish these directional effects. Operator 4 performs best overall as the is one closest to zero, whereas Operator 9 —previously ranked highest— now sits in fourth place.

Missed Flaws

Not all operators missed sizing a flaw but those who missed sizing the flaw were targeting almost the same flaw two operators missed sizing defect A, the same operator missed sizing defects B and C and a different operator missed sizing defect F, these results can be seen in the table 4.

Table 4. Table showing which operators missed defects

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

Now using MATLAB to determine this same inaccuracy, the operators were put to a test and are shown in table 5 below. To show which operator missed sizing any flaw and how many the them were missed.

Table 5. Table showing which operators missed defects

Operator	Times_Y_Zero
{ 'Op1' }	0
{ 'Op2' }	3
{ 'Op3' }	0
{ 'Op4' }	0
{ 'Op5' }	0
{ 'Op6' }	1
{ 'Op7' }	0
{ 'Op8' }	0
{ 'Op9' }	1
{ 'Op10' }	0

The table shows that only 3 operators —Op3, Op6, and Op9— failed to detect a defect. Previously, Op9 was regarded as the top due to its low measurement error. However, this oversight in identifying a flaw is significantly undermines its overall performance.

In a real-world scenario, missing a critical defect in a building component or essential pipeline could result in catastrophic consequences, potentially endangering lives and causing property damage. So for the next categories, these 3 operations won't be taking into account those values, but also won't be taken into account for any further overall performance rating.

Consistency

Consistency is key, to measure consistency is to ask the proper question, what type of consistency? In this case, each operator can be measured in how consistent by taking the gradient as close to one as possible. If the gradient (slope) of the operator's line is 1, it indicates that, on average, the operator's measured values increase at the same rate as the actual defect sizes. For every millimetre increase in the true size of the flaw, the operator's measurement also increases by that amount.

Adding more weight for being consistent; was possible to exclude the values when the operator missed a flaw not being taken into account for the trend line. In the following graphs (figure 2) can be seen 2 operators with different gradients to their slope for the data collected.

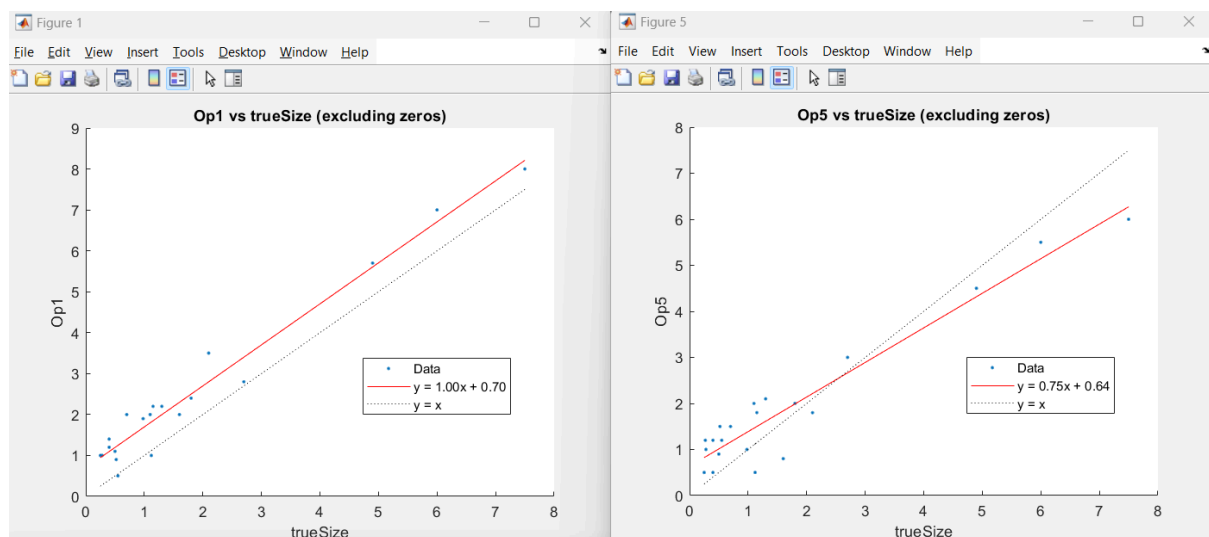


Figure 2. The gradient of the trendline comparison for the closest and furthest to 1

In the two graphs, Operator 1 demonstrates strong consistency, indicated by a gradient of 1.0021. This result suggests the presence of only a minor offset, potentially due to factors such as equipment calibration issues or the technician repeatedly making the same small-scale error, this can happen to experienced technicians who always do the same job repeatedly creating an error called “familiarity blindness” when they no longer notice small mistakes or flaws.

In contrast, Operator 5, with a gradient of 0.7513, deviates substantially from the $y=x$ line. Even after considering the offset (represented by the intercept, b), Operator 5's trendline would not align closely with the ideal one-to-one relationship, indicating poorer consistency in measuring flaw sizes.

Now this consideration focuses on the best and worst cases. What about the others? How do their gradients and offsets compare? To address these questions, Table 6 provides the list of all operators, including their respective trendline questions.

Table 6. Operators ranked by the value of their gradient (m) excluding their flaws (their zero measurements)

Operator	m	b
{ 'Op5' }	{ '0.7513' }	{ '0.6364' }
{ 'Op3' }	{ '0.8056' }	{ '0.7240' }
{ 'Op9' }	{ '0.8110' }	{ '0.3757' }
{ 'Op6' }	{ '0.8442' }	{ '0.3684' }
{ 'Op10' }	{ '0.8727' }	{ '0.9704' }
{ 'Op2' }	{ '0.8747' }	{ '0.6502' }
{ 'Op8' }	{ '0.8911' }	{ '0.3292' }
{ 'Op4' }	{ '0.8968' }	{ '0.4921' }
{ 'Op7' }	{ '0.9945' }	{ '0.5132' }
{ 'Op1' }	{ '1.0021' }	{ '0.6954' }

Notably, most operators (7 out of 10) fell within a gradient range of approximately $[0.84 - 1]$. This suggests that the majority of the technicians demonstrated a tendency to increase their measured values in close proportion to the actual flaw sizes, though not perfectly. When considering whether $[0.84 - 1]$ is a good range for comparison, the decision depends on how strictly the relationship needs to mirror a one-to-one to $m = 1$.

Operators who are almost exact would say that are between $[0.95 - 1]$ (shown in the red box) and those who are just moderately close are $[0.84-0.94]$ (shown in the blue box) which narrows the gap between the best operators and the moderately good ones. The other ones won't be taken into account as the gradient differs as much as $[0.19 - 0.25]$ from its value to the value of 1.

Offset

The offset value as mentioned previously corresponds to the “b” parameter in each operator’s trendline equation. Table 7 demonstrates that even operators with similar gradients can have substantially different offsets. For instance, while Operator 1’s gradient is 1.0021 and its offset is 0.6954, Operator 7’s gradient of 0.9945 corresponds to an offset of just 0.5132.

These two offset values share no evident similarity, suggesting that, although the gradients may be nearly identical, the offset component introduces a distinct variation in how each operator’s measurements align with the correct sizing.

Table 7. Operators ranked by the value of their gradient (m) excluding their flaws (their zero measurements)

Operator	m	b
{ 'Op5' }	{ '0.7513' }	{ '0.6364' }
{ 'Op3' }	{ '0.8056' }	{ '0.7240' }
{ 'Op9' }	{ '0.8110' }	{ '0.3757' }
{ 'Op6' }	{ '0.8442' }	{ '0.3684' }
{ 'Op10' }	{ '0.8727' }	{ '0.9704' }
{ 'Op2' }	{ '0.8747' }	{ '0.6502' }
{ 'Op8' }	{ '0.8911' }	{ '0.3292' }
{ 'Op4' }	{ '0.8968' }	{ '0.4921' }
{ 'Op7' }	{ '0.9945' }	{ '0.5132' }
{ 'Op1' }	{ '1.0021' }	{ '0.6954' }

Upon examining the top four technicians as presented in Table 7, a subtle yet small pattern shows. As the gradient values diverge from 1, it progressively decreases towards zero. This observation can indicate that even slight deviations from the ideal $y = x$ affect all parameters of the trendline. But that only can be said of the first 4 operators, the other ones do not follow this trend which leads to no further investigation regarding this matter.

Regardless of the small trend, if those 4 operators or even the 10 operators do shift by the amount of their “b” that would mean that they would have a spot on the right size for each flaw with minimal error. Using as an example Operator 1 and shifting the curve by 0.6954.

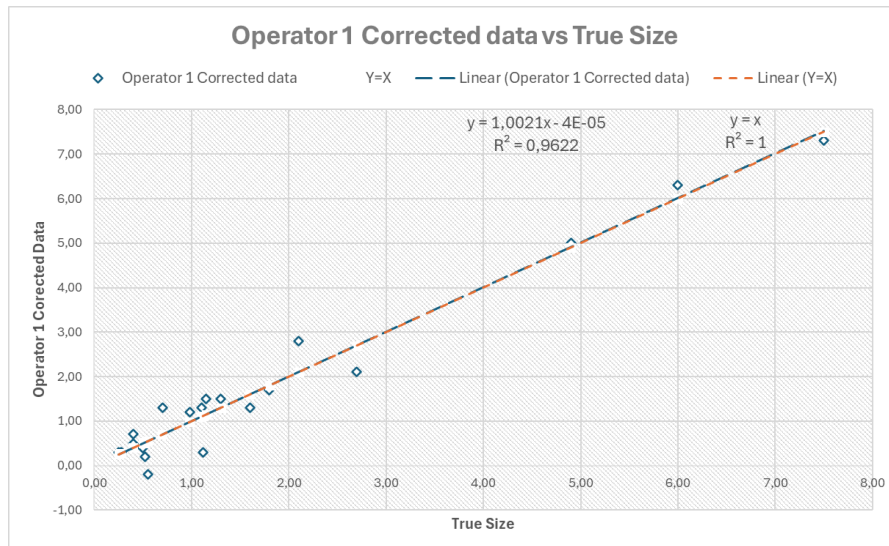


Figure 3. Operator 1 Corrected data vs True Size

It can be seen that shifting the operators' values to the same amount of "b" gave an almost perfect line (equation for the line). The average error using the corrected values is now -0.004 . Using MATLAB to create the 95% Confidence Intervals for the first Operator, the result is displayed in Figure 4.

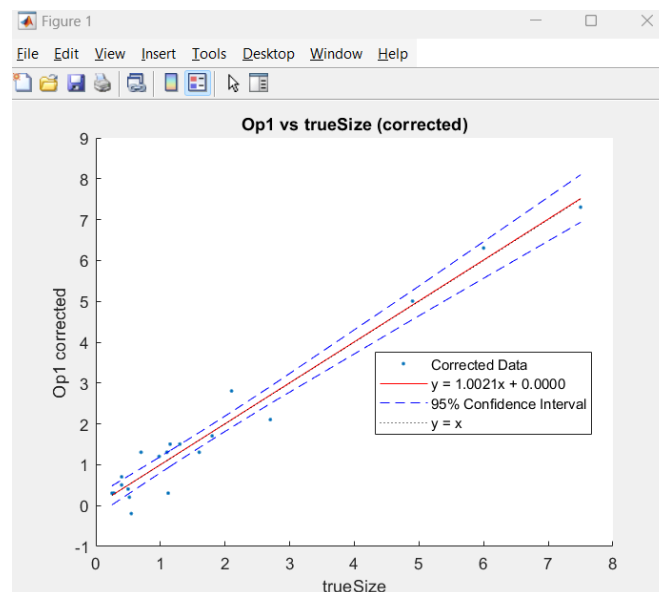


Figure 4. Op1 vs True Size (Corrected values) including 95% Confidence Intervals

The number of points shown inside the 95% confidence interval for Op1 is 9 of a total of 21 points which is 42.857% inside the confidence interval. Doing this for all operators Table 8 displays these values inside the new CI for each technician.

Table 8. Number of values inside the 95% CI (corrected data)

Operator	ValuesInsideCI	TotalPoints	PercentageInside
{ 'Op1' }	9	21	42.857
{ 'Op2' }	9	21	42.857
{ 'Op3' }	13	21	61.905
{ 'Op4' }	11	21	52.381
{ 'Op5' }	7	21	33.333
{ 'Op6' }	8	21	38.095
{ 'Op7' }	8	21	38.095
{ 'Op8' }	10	21	47.619
{ 'Op9' }	9	21	42.857
{ 'Op10' }	10	21	47.619

Even the top technicians exhibit a relatively low proportion of measurements within the 95% CI. However, after applying the offset correction (“b” value shift), the error decreases substantially for Operators 1 and 7. Referring to the updated table and assuming a normal distribution of these values, Figure 5 illustrates the lowest percentage found is approximately 33.333% (shown in the red box) while the highest reaches about 61.905% (shown in the blue box).

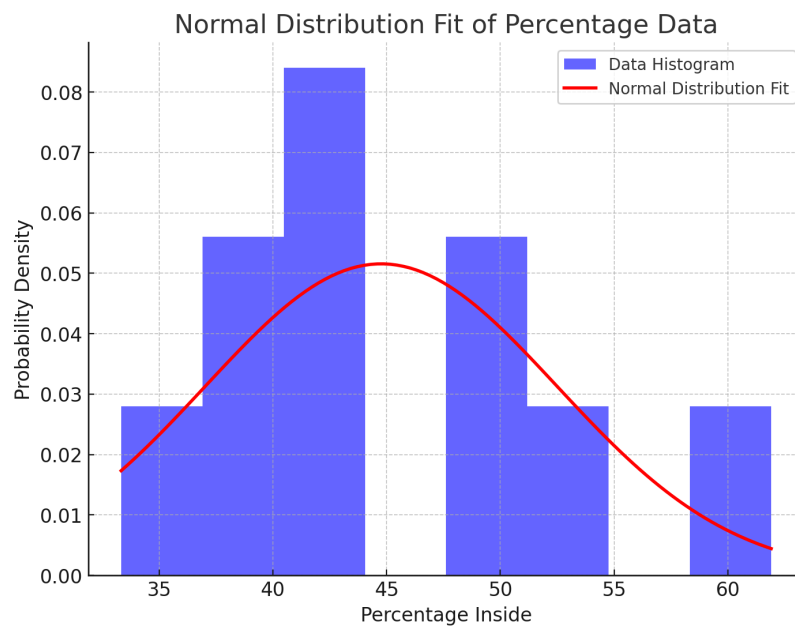


Figure 5. Normal Distribution Fir of Percentage Data (with corrected data)

Considering that Operator 1 frequently appears among the top performers concerning consistency, its proportion of data points within the 95% confidence interval remains approximately in line with the group’s average which is 44.762.

Undersizing/Oversizing

Undersizing and Oversizing can be explained in a few words, but understanding that oversizing the same amount as undersizing in different contexts can be completely different things. In this case over/undersized as it is a statistical analysis if an Op oversizes a flaw but 0.5 and then a next measurement this same Op gave a -0.5 (undersize) the average of this operator would be 0. But taking this a step further determining the before and after is shown in table 9.

Table 9. Operator Over/Undersizing table (corrected data) with Avg Difference (before and after)

Operator	PointsAbove	PointsBelow	PercentAbove	PercentBelow	Category	AvgDifference	AvgDifferenceBefore
{ 'Op1' }	13	8	61.905	38.095	{ 'Oversizer' }	0.24849	0.78158
{ 'Op2' }	5	16	23.81	76.19	{ 'Undersizer' }	-0.51273	-0.26429
{ 'Op3' }	4	17	19.048	80.952	{ 'Undersizer' }	-0.46809	-0.525
{ 'Op4' }	4	17	19.048	80.952	{ 'Undersizer' }	-0.23521	-0.195
{ 'Op5' }	9	12	42.857	57.143	{ 'Undersizer' }	-0.8739	-0.68667
{ 'Op6' }	6	15	28.571	71.429	{ 'Undersizer' }	-0.51308	-0.4625
{ 'Op7' }	10	11	47.619	52.381	{ 'Undersizer' }	-0.19684	-0.1
{ 'Op8' }	9	12	42.857	57.143	{ 'Undersizer' }	-0.47004	-0.49
{ 'Op9' }	7	14	33.333	66.667	{ 'Undersizer' }	-0.65997	-0.488
{ 'Op10' }	7	14	33.333	66.667	{ 'Undersizer' }	-0.41967	-0.6

As it looks from the table using the average error for the before and after data looked that it didn't help but 2 operators, Op1 and Op9, if this is taken from a different view and looking at the absolute value which can be shown in table 10.

Table 10. Average Absolute Error before and after correction

Operator	AvgAbsErrorBefore	AvgAbsErrorAfter
{ 'Op1' }	0.71524	0.30396
{ 'Op2' }	0.48476	0.43964
{ 'Op3' }	0.58952	0.42341
{ 'Op4' }	0.37033	0.20334
{ 'Op5' }	0.60095	0.57091
{ 'Op6' }	0.42524	0.43741
{ 'Op7' }	0.51333	0.19682
{ 'Op8' }	0.37524	0.34989
{ 'Op9' }	0.4781	0.51761
{ 'Op10' }	0.80857	0.34061

Now clearly shifting the values by the amount of “b” from their initial trendlines reduced the error substantially. This reduced the under/oversizing error range, also using the information from previous tables it was possible to determine that previously the Operators were all Oversizing but now 9 out of 10 are undersizing and just 1 is oversizing shown in the blue box above in table 9.

Results and Discussion

After thoroughly analysing all stages of the statistical analysis, the data-driven approach showed that Operators 2,6, and 8 missed detecting between 1 and 3 flaws out of the total 10. Such an oversight is not acceptable, especially for critical applications (e.g., structural components of a bridge or a hospital facility). Removing these three, it is left Operators 1,3,4,5,7,9 and 10. Just like in King's Lynn Hospital in November 2022 where the material had serious weaknesses and deteriorating (King's Lynn hospital patients fear roof collapse - health watchdog, 2022).

Among these remaining operators, Operators 9,5, and 3 showed the largest absolute errors -ranging in their corrected absolute errors above the group's median - thus eliminating them as possible best operators. This filtering process narrowed the selection process to Operators 1,4 and 7. Evaluating their gradients, which quantitatively measures how closely their measurements scale to the actual sizes (with a perfect gradient being 1), indicated that only two operators, 1 and 7, demonstrated near-ideal consistency.

Analyzing how the values of R^2 presented for each operator, between the top 2 technicians, Op7 performs slightly better than Op1 knowing that the R^2 values are how the trend line model predicts the behaviour of the data (Brown, 2001).

Table 11. Operator Performance Table

Weight Distribution Criteria for Technician Ranking						
Rank	Operator	Missed Flaws? (20%)	R^2 Value (30%)	Gradient (40%)	95% CI Coverage (10%)	Final Score (100%)
1	Op7	No	0,98393	0,9945	0,38095	0,9311
2	Op1	No	0,96222	0,9979	0,42857	0,930683
3	Op4	No	0,99252	0,8911	0,52381	0,906577
4	Op10	No	0,96302	0,8727	0,47619	0,885605
5	Op3	No	0,94846	0,8056	0,61905	0,868683
6	Op9	No	0,93809	0,811	0,42857	0,848684
7	Op5	No	0,95186	0,7513	0,33333	0,8194
8	Op8	Yes	0,95186	0,8911	0,47619	0,6896
9	Op2	Yes	0,94755	0,8747	0,42857	0,6770
10	Op6	Yes	0,94197	0,8442	0,38095	0,6584

Subsequently, examining the 95% confidence intervals and counting the proportion of data points within these bounds - where the best operators achieved a range between roughly 40% to 60% coverage- showed that operator 1 placed a higher percentage of values inside this interval than operator 7. Leaving Operator 7 as the most accurate at sizing flaws if only a shift of its values were down by a constant amount of 0.5132 of b.

Conclusion

After a detailed, multi-stage statistical analysis, it became evident that not all technicians were suitable for crucial applications. Operators who failed to detect flaws were excluded first, followed by those who showed persistently high absolute errors, even after data corrections. Among the remaining candidates, further assessments of gradient accuracy and the percentage of values falling within the 95% confidence intervals helped pinpoint the top performers. Although Operator 7 initially appeared promising, the presence of numerous identical recorded values raised concerns about the reliability of their measurements.

Ultimately, Operator 1 emerged as the most accurate and dependable operator, consistently meeting the required standards across all evaluated metrics. This outcome underlines the importance of a comprehensive and step-by-step analytical framework when selecting the most suitable technician for essential ultrasonic flaw detection tasks.

For reference to all the code to be made possible for the analysis please look for the Appendix, as well for all the graphs for before and after the corrected values.

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Appendix 1: MATLAB Code

```
%%
close all;
clc;
% Assuming your table is named "operators" and includes columns:
% Defect, trueSize, Op1, Op2, ..., Op10
numOperators = 10;
% Count how many zeros each operator has
zeroCounts = zeros(numOperators,1);
for i = 1:numOperators
    yData = operators.(sprintf('Op%d', i));
    zeroCounts(i) = sum(yData == 0);
end
% Create and display the zero counts table
operatorNames = arrayfun(@(x) sprintf('Op%d', x), 1:numOperators,
'UniformOutput', false)';
zeroTable = table(operatorNames, zeroCounts, 'VariableNames', {'Operator',
'Times_Y_Zero'});
disp('Table of Operators and how many times Y=0:');
disp(zeroTable);
formulas = cell(numOperators, 1);
% Prepare arrays for summary metrics
avgErrorValues = zeros(numOperators,1);
avgAbsErrorValues = zeros(numOperators,1);
avgPercErrorValues = zeros(numOperators,1);
% Arrays to store m and b for each operator
mValues = zeros(numOperators,1);
bValues = zeros(numOperators,1);
for i = 1:numOperators
    % Extract current operator data
    yDataAll = operators.(sprintf('Op%d', i));
    xDataAll = operators.trueSize;

    % Filter out rows where y=0 for this operator
    validIdx = (yDataAll ~= 0);
    xData = xDataAll(validIdx);
    yData = yDataAll(validIdx);

    % Fit a linear model (y = mx + b)
    mdl = fitlm(xData, yData);
    coefficients = mdl.Coefficients.Estimate;
    m = coefficients(2); % Slope
    b = coefficients(1); % Intercept

    % Store m and b
    mValues(i) = m;
    bValues(i) = b;

    [yFit, yCI] = predict(mdl, xData, 'Alpha', 0.05);
    yLower = yCI(:,1);
    yUpper = yCI(:,2);
end
```

```

% Format the trend line formula string
if b >= 0
    formulas{i} = sprintf('y = %.2fx + %.2f', m, b);
else
    formulas{i} = sprintf('y = %.2fx - %.2f', m, abs(b));
end

% Create a new figure for each operator plot
% figure;
hold on;
plot(xData, yData, '.', 'DisplayName', 'Data');
plot(xData, yFit, '-r', 'DisplayName', formulas{i});
plot(xData, yUpper, '--b', 'DisplayName', '95% Confidence Interval');
plot(xData, yLower, '--b', 'HandleVisibility', 'off');
plot(xData, xData, ':k', 'DisplayName', 'y = x');
title(sprintf('Op%d vs trueSize (excluding zeros)', i));
xlabel('trueSize');
ylabel(sprintf('Op%d', i));
legend('Location', 'best');
% hold off;

% --- Compute error metrics ---
% Error = trueSize - OperatorValue
errorValues = xData - yData;
% Absolute Error
absErrorValues = abs(errorValues);
% Percentage Error = (OperatorValue / trueSize)*100
percErrorValues = (yData ./ xData)*100;

% Compute averages
avgError = mean(errorValues);
avgAbsError = mean(absErrorValues);
avgPercError = mean(percErrorValues);

% Store these average values
avgErrorValues(i) = avgError;
avgAbsErrorValues(i) = avgAbsError;
avgPercErrorValues(i) = avgPercError;

% Create and display the error table for this operator
defectNames = operators.Defect(validIdx);
errorTable = table(defectNames, xData, yData, errorValues, absErrorValues,
percErrorValues, ...
    'VariableNames',
{'Defect', 'trueSize', 'OperatorValue', 'Error', 'AbsoluteError', 'PercentageError'});

disp(['Error table for ', operatorNames{i}, ':']);
disp(errorTable);

% Display the three average values for this operator
disp(['For ', operatorNames{i}, ':']);

```

```

disp(['Average Error: ', num2str(avgError)]);
disp(['Average Absolute Error: ', num2str(avgAbsError)]);
disp(['Average Percentage Error: ', num2str(avgPercError)]);
disp('-----');
end
% Display the trend line formulas after excluding zero values
trendTable = table(operatorNames, formulas, 'VariableNames', {'Operator',
'Trend_Line_Formula'});
disp('Trend line formulas after excluding zero values:');
disp(trendTable);
% Create summary table of average errors per operator
summaryTable = table(operatorNames, avgErrorValues, avgAbsErrorValues,
avgPercErrorValues, ...
'VariableNames', {'Operator', 'AvgError', 'AvgAbsError', 'AvgPercError'});
disp('Summary of average errors per operator:');
disp(summaryTable);
% Create ranking tables based on each metric
errorRanking = sortrows(summaryTable, 'AvgError', 'ascend');
absErrorRanking = sortrows(summaryTable, 'AvgAbsError', 'ascend');
percErrorRanking = sortrows(summaryTable, 'AvgPercError', 'ascend');
% Reduced tables only with relevant columns
errorRankingReduced = errorRanking(:, {'Operator', 'AvgError'});
absErrorRankingReduced = absErrorRanking(:, {'Operator', 'AvgAbsError'});
percErrorRankingReduced = percErrorRanking(:, {'Operator', 'AvgPercError'});
disp('Operators ranked by Average Error (just these values):');
disp(errorRankingReduced);
disp('Operators ranked by Average Absolute Error (just these values):');
disp(absErrorRankingReduced);
disp('Operators ranked by Average Percentage Error (just these values):');
disp(percErrorRankingReduced);
% Compute combined rank based on average of positions
allOps = summaryTable.Operator;
combinedRank = zeros(numOperators,1);
for i = 1:numOperators
    currentOp = allOps{i};
    errorPos = find(strcmp(errorRankingReduced.Operator, currentOp));
    absErrorPos = find(strcmp(absErrorRankingReduced.Operator, currentOp));
    percErrorPos = find(strcmp(percErrorRankingReduced.Operator, currentOp));
    avgPos = (errorPos + absErrorPos + percErrorPos) / 3;
    combinedRank(i) = avgPos;
end
combinedRankTable = table(allOps, combinedRank, 'VariableNames',
{'Operator', 'AverageRankPosition'});
combinedRankTable = sortrows(combinedRankTable, 'AverageRankPosition',
'ascend');
disp('Final ranking based on the average rank position across all three
metrics:');
disp(combinedRankTable);
% Now create a new rank table for the value of m and display m,b with 4
decimal places
coefficientTable = table(operatorNames, mValues, bValues, 'VariableNames',
{'Operator', 'm', 'b'});
% Sort by m (ascending)

```

```

mRanking = sortrows(coefficientsTable, 'm', 'ascend');
% Convert m and b to strings with 4 decimal places
mFormatted = arrayfun(@(x) sprintf('%.4f', x), mRanking.m, 'UniformOutput',
false);
bFormatted = arrayfun(@(x) sprintf('%.4f', x), mRanking.b, 'UniformOutput',
false);
mRankingFormatted = table(mRanking.Operator, mFormatted, bFormatted, ...
'VariableNames', {'Operator', 'm', 'b'});
disp('Operators ranked by the value of m (gradient):');
disp(mRankingFormatted);
% Sum of all m values
sumOfM = sum(mValues);
% Average of all m values
averageM = sumOfM / numOperators;
% Sum of all b values
sumOfB = sum(bValues);
% Average of b values
averageB = sumOfB / numOperators;
disp(['Sum of all m values: ', num2str(sumOfM)]);
disp(['Average of m values: ', num2str(averageM)]);
disp(['Sum of all b values: ', num2str(sumOfB)]);
disp(['Average of b values: ', num2str(averageB)]);
% Initialize arrays to store results
numOperators = 10; % Number of operators
aboveCount = zeros(numOperators, 1); % Count of points above y=x
belowCount = zeros(numOperators, 1); % Count of points below y=x
totalPoints = length(trueSize); % Total number of points
percentAbove = zeros(numOperators, 1); % Percentage above y=x
percentBelow = zeros(numOperators, 1); % Percentage below y=x
category = cell(numOperators, 1); % Oversizer/Undersizer category
% Loop through each operator column (Op1 to Op10)
for i = 1:numOperators
    % Extract the current operator column
    yData = operators.(sprintf('Op%d', i)); % Dynamically select 'Op1' to
'Op10'
    xData = trueSize; % Use 'trueSize' as the x-axis values

    % Calculate the counts above and below y = x
    aboveCount(i) = sum(yData > xData);
    belowCount(i) = sum(yData < xData);

    % Calculate percentages
    percentAbove(i) = (aboveCount(i) / totalPoints) * 100;
    percentBelow(i) = (belowCount(i) / totalPoints) * 100;

    % Determine category
    if percentAbove(i) > percentBelow(i)
        category{i} = 'Oversizer';
    else
        category{i} = 'Undersizer';
    end
end
% Create the result table

```

```

resultTable = table( ...
    arrayfun(@(x) sprintf('Op%d', x), 1:numOperators, 'UniformOutput',
false)', ...
    aboveCount, belowCount, percentAbove, percentBelow, category, ...
    'VariableNames', {'Operator', 'PointsAbove', 'PointsBelow',
'PercentAbove', 'PercentBelow', 'Category'});
% Display the table
disp('Operator Over/Under Sizing Table:');
disp(resultTable);
% Overall summary across all operators
overallAbove = sum(aboveCount);
overallBelow = sum(belowCount);
overallPercentAbove = (overallAbove / (numOperators * totalPoints)) * 100;
overallPercentBelow = (overallBelow / (numOperators * totalPoints)) * 100;
% Create the summary table
summaryTable = table(overallAbove, overallBelow, overallPercentAbove,
overallPercentBelow, ...
    'VariableNames', {'TotalPointsAbove', 'TotalPointsBelow',
'OverallPercentAbove', 'OverallPercentBelow'});
% Display the summary table
disp('Overall Over/Under Sizing Summary:');
disp(summaryTable);
% ---- Add the corrected values section here ----
% Create a copy of the operators table to store corrected values
correctedOperators = operators;
% Loop through each operator and adjust the values by subtracting the
intercept b
for i = 1:numOperators
    opName = operatorNames{i};    % e.g. 'Op1'
    correctedOperators.(opName) = operators.(opName) - bValues(i);
end
disp('Corrected Operators Table (values adjusted by subtracting their
respective b):');
disp(correctedOperators);
% ---- Create new graphs with corrected values and 95% CI ----
for i = 1:numOperators
    opName = operatorNames{i};
    yDataCorrected = correctedOperators.(opName);    % Corrected operator values
    xData = correctedOperators.trueSize;            % trueSize remains
unchanged

    % Fit a linear model with the corrected data
    mdlCorrected = fitlm(xData, yDataCorrected);
    coeffCorrected = mdlCorrected.Coefficients.Estimate;
    mCorr = coeffCorrected(2);
    bCorr = coeffCorrected(1);

    % Predict fitted line and 95% confidence intervals
    [yFitCorr, yCICorr] = predict(mdlCorrected, xData, 'Alpha', 0.05);

    % Format the trend line equation string depending on the sign of bCorr
    if bCorr >= 0
        trendEq = sprintf('y = %.4fx + %.4f', mCorr, bCorr);
    else
        trendEq = sprintf('y = %.4fx - %.4f', mCorr, -bCorr);
    end
end

```

```

else
    trendEq = sprintf('y = %.4fx - %.4f', mCorr, abs(bCorr));
end

% Plot the corrected data and new trend line with 95% CI
figure;
hold on;
plot(xData, yDataCorrected, '.', 'DisplayName', 'Corrected Data');
plot(xData, yFitCorr, '-r', 'DisplayName', trendEq);
plot(xData, yCICorr(:,1), '--b', 'DisplayName', '95% Confidence
Interval');
plot(xData, yCICorr(:,2), '--b', 'HandleVisibility', 'off');
plot(xData, xData, ':k', 'DisplayName', 'y = x');

xlabel('trueSize');
ylabel(sprintf('%s corrected', opName));
title(sprintf('%s vs trueSize (corrected)', opName));
legend('Location', 'best');
hold off;
end

% Preallocate arrays for results
insideCountArray = zeros(numOperators,1);
totalPointsArray = zeros(numOperators,1);
percentageInsideArray = zeros(numOperators,1);
for i = 1:numOperators
    opName = operatorNames{i};
    yDataCorrected = correctedOperators.(opName);
    xData = correctedOperators.trueSize;

    % Fit a linear model with the corrected data again for consistency
    mdlCorrected = fitlm(xData, yDataCorrected);
    [yFitCorr, yCICorr] = predict(mdlCorrected, xData, 'Alpha', 0.05);

    % Determine how many points are inside the 95% CI
    insideMask = (yDataCorrected >= yCICorr(:,1)) & (yDataCorrected <=
yCICorr(:,2));
    insideCount = sum(insideMask);
    totalPoints = length(yDataCorrected);
    percentageInside = (insideCount / totalPoints) * 100;

    insideCountArray(i) = insideCount;
    totalPointsArray(i) = totalPoints;
    percentageInsideArray(i) = percentageInside;
end

% Create a table with the results
CI_Table = table(operatorNames, insideCountArray, totalPointsArray,
percentageInsideArray, ...
    'VariableNames', {'Operator', 'ValuesInsideCI', 'TotalPoints',
'PercentageInside'});
disp('Number of values inside the 95% Confidence Intervals (Corrected
Data):');
disp(CI_Table);

```

```

% --- Oversizing/Undersizing Analysis for Corrected Data with Average
Difference ---
aboveCount_corrected = zeros(numOperators, 1);
belowCount_corrected = zeros(numOperators, 1);
percentAbove_corrected = zeros(numOperators, 1);
percentBelow_corrected = zeros(numOperators, 1);
category_corrected = cell(numOperators, 1);
avgDifference_corrected = zeros(numOperators, 1);
avgDifference_before = zeros(numOperators, 1);
xData = correctedOperators.trueSize;
totalPoints_corrected = length(xData);
for i = 1:numOperators
    opName = operatorNames{i};
    yDataCorrected = correctedOperators.(opName);

    % Differences after correction
    differences = yDataCorrected - xData;

    % Differences before correction
    yDataOriginal = operators.(opName);
    differencesBefore = yDataOriginal - operators.trueSize;

    % Masks for above and below the line after correction
    aboveMask = differences > 0;
    belowMask = differences < 0;

    aboveCount_corrected(i) = sum(aboveMask);
    belowCount_corrected(i) = sum(belowMask);

    percentAbove_corrected(i) = (aboveCount_corrected(i) /
totalPoints_corrected) * 100;
    percentBelow_corrected(i) = (belowCount_corrected(i) /
totalPoints_corrected) * 100;

    % Determine category and compute average differences
    if percentAbove_corrected(i) > percentBelow_corrected(i)
        category_corrected{i} = 'Oversizer';

        % Average difference after correction (oversize = positive diffs only)
        if any(aboveMask)
            avgDifference_corrected(i) = mean(differences(aboveMask));
        else
            avgDifference_corrected(i) = 0;
        end

        % Average difference before correction for oversizer
        % Use the same mask (aboveMask), but now applied to differencesBefore
        aboveMaskBefore = differencesBefore > 0;
        if any(aboveMaskBefore)
            avgDifference_before(i) =
mean(differencesBefore(aboveMaskBefore));
        else
            avgDifference_before(i) = 0;
        end
    end
end

```

```

        end

    else
        category_corrected{i} = 'Undersizer';

        % Average difference after correction (undersize = negative diffs
only)
        if any(belowMask)
            avgDifference_corrected(i) = mean(differences(belowMask));
        else
            avgDifference_corrected(i) = 0;
        end

        % Average difference before correction for undersizer
        % Use a similar mask for before correction
        belowMaskBefore = differencesBefore < 0;
        if any(belowMaskBefore)
            avgDifference_before(i) =
mean(differencesBefore(belowMaskBefore));
        else
            avgDifference_before(i) = 0;
        end
    end
end

% Update the table to include the before correction difference column
oversizeUndersizeCorrectedTable = table(operatorNames, aboveCount_corrected,
belowCount_corrected, ...
    percentAbove_corrected, percentBelow_corrected, category_corrected,
avgDifference_corrected, avgDifference_before, ...
    'VariableNames', {'Operator', 'PointsAbove', 'PointsBelow',
'PercentAbove', 'PercentBelow', 'Category', 'AvgDifference',
'AvgDifferenceBefore'});
disp('Operator Over/Under Sizing Table (Corrected Data) with Average
Difference (before and after):');
disp(oversizeUndersizeCorrectedTable);
% Preallocate arrays for storing average absolute errors before and after
correction
avgAbsErrorBefore = zeros(numOperators,1);
avgAbsErrorAfter = zeros(numOperators,1);
xData = correctedOperators.trueSize; % The trueSize column remains the same
for i = 1:numOperators
    opName = operatorNames{i};

    % Original data before correction
    yDataOriginal = operators.(opName);
    % Corrected data after offset removal
    yDataCorrected = correctedOperators.(opName);

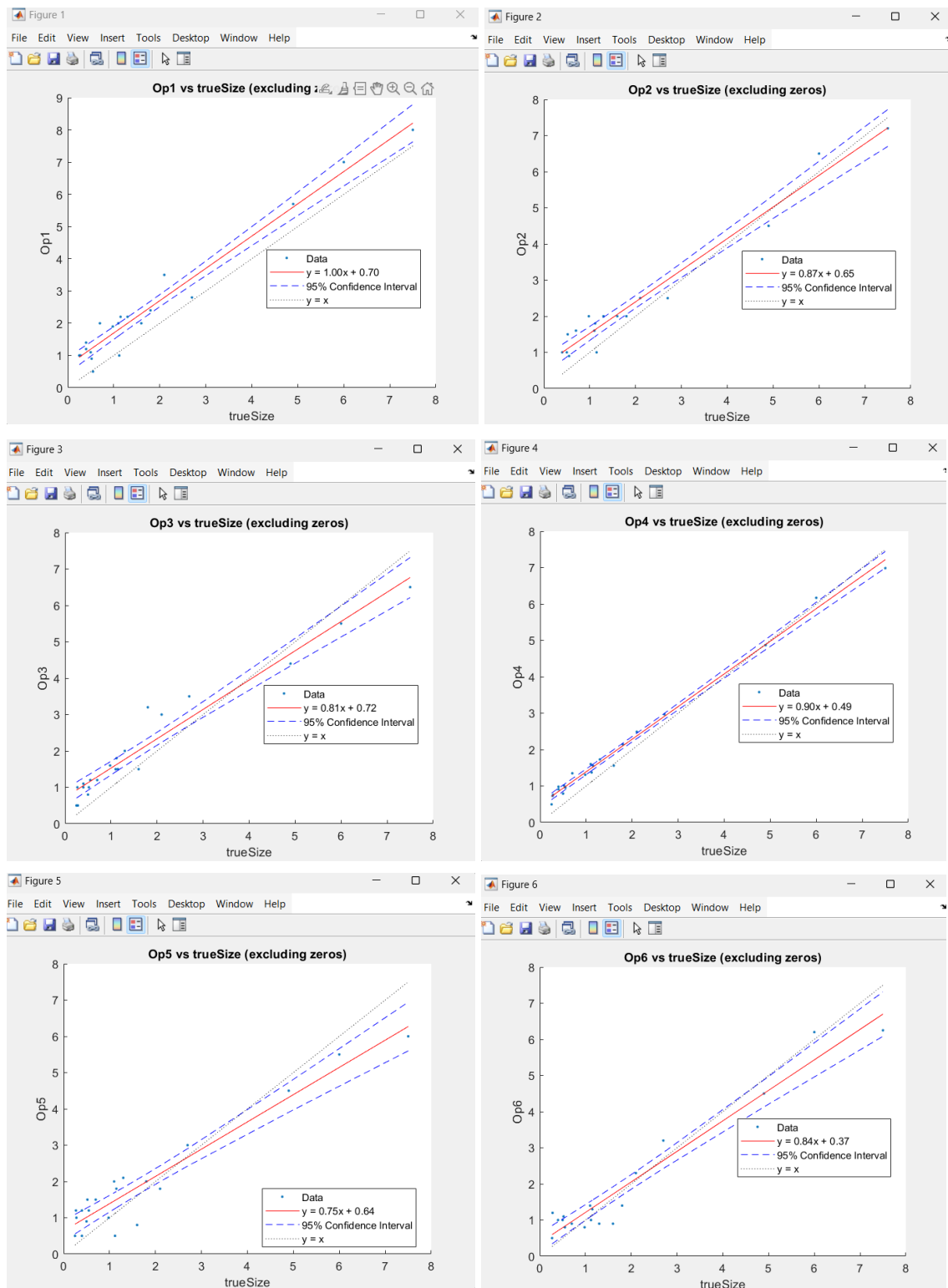
    % Compute average absolute error before correction
    avgAbsErrorBefore(i) = mean(abs(yDataOriginal - xData));

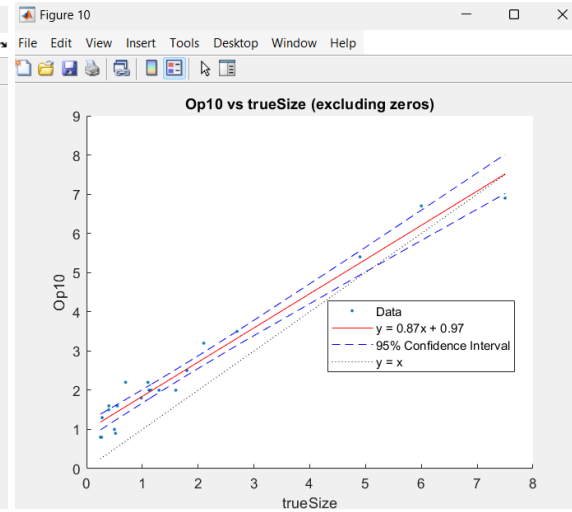
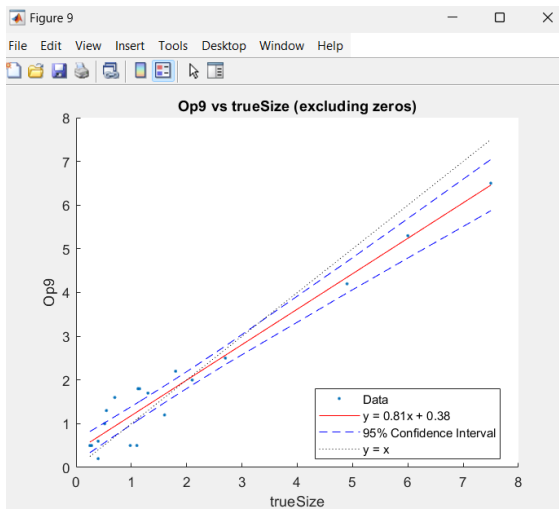
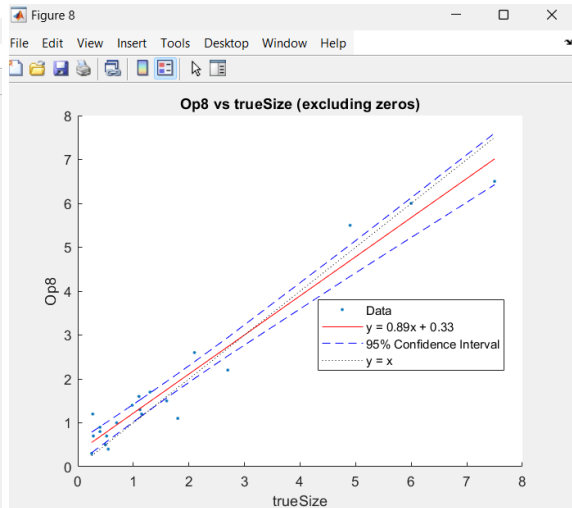
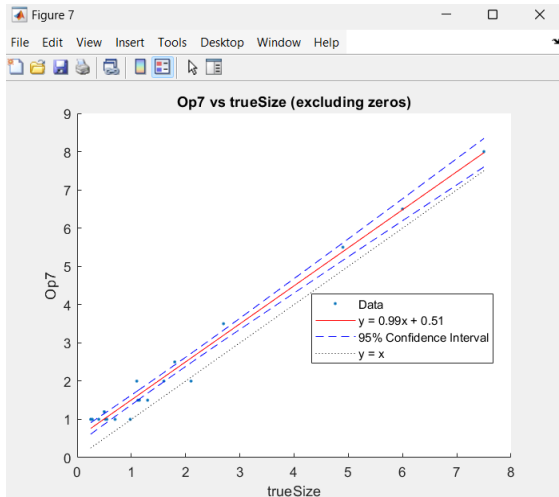
    % Compute average absolute error after correction
    avgAbsErrorAfter(i) = mean(abs(yDataCorrected - xData));

```

```
end
% Create a table with these values
absErrorComparisonTable = table(operatorNames, avgAbsErrorBefore,
avgAbsErrorAfter, ...
    'VariableNames', {'Operator','AvgAbsErrorBefore','AvgAbsErrorAfter'});
disp('Average Absolute Error Before and After Correction:');
disp(absErrorComparisonTable);
```

Appendix 2: Graphs Before the Corrected Data





Appendix 3: Graphs After the Corrected Data

