

MSc Motorsport Engineering

Through Wall Sizing Accuracy Analysis Report

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Abstract

A statistical analysis of the given POD (probability of detection) dataset was carried out in order to determine the effectiveness of each technician and of the general procedure. A series of techniques and data visualisations were used to compare the data, including a boxplot graph to give a comparison between each technician's data, a bar chart of the mean and mean absolute values, linear regression techniques, and true line comparisons and y-offset trendline comparisons, which all served to compare each technician's accuracy. Finally, the discrete number of entries that over or underestimated defect size was also extracted from the dataset, which served more to assess the accuracy of the procedure itself. It was ultimately found that while all technicians tended to overestimate defect size, technician 4 appeared to be the most accurate with the lowest absolute mean error and a small trendline variance.

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Apparatus

- Microsoft Excel

Procedure

This experiment concerns a given dataset gathered as part of a larger probability of detection (POD) study. The purpose of the experiment is to assess the performance of a new procedure for gauging thickness ultrasonically. Through statistical analysis and linear regression, the accuracy of each technician and of the equipment and procedure will be analysed. The method through which the data was acquired is not specified, although the design of the testing itself is, in industry, interdependent with the analysis of the results (Parker, et al., 2022).

Measurements

The given dataset is shown below:

Table 1 - Table showing the given operator data upon which the analysis was carried out

Defect	True Size	Op1	Op2	Op3	Op4	Op5	Op6	Op7	Op8	Op9	Op10
A	0.25	1	0	0.5	0.5	0.5	0	1	0.3	0.5	0.8
B	0.27	1	0	1	0.73	1.2	0.5	1	1.2	0.5	0.8
C	0.28	1	0	0.5	0.76	1	1.2	1	0.7	0.5	1.3
D	0.4	1.2	1	1	0.91	0.5	1	1	0.8	0.6	1.5
E	0.4	1.4	1	1.1	0.98	1.2	1	1	0.9	0.2	1.6
F	0.5	1.1	1	0.8	0.79	0.9	1	1.2	0.5	0	1
G	0.52	0.9	1.5	1	1.01	1.5	1.1	1	0.7	1	0.9
H	0.55	0.5	0.9	1.2	0.96	1.2	0.8	1	0.4	1.3	1.6
I	0.7	2	1.6	1.2	1.35	1.5	0.9	1	1	1.6	2.2
J	0.98	1.9	2	1.6	1.31	1	0.8	1	1.4	0.5	1.8
K	1.12	1	1.8	1.8	1.37	0.5	1	1.5	1.3	1.8	2
L	1.15	2.2	1	1.5	1.56	1.8	1.3	1.5	1.2	1.8	2
M	1.1	2	1.6	1.5	1.6	2	1.4	2	1.6	0.5	2.2
N	1.3	2.2	2	2	1.73	2.1	0.9	1.5	1.7	1.7	2
O	1.6	2	2	1.5	1.56	0.8	0.9	2	1.5	1.2	2
P	1.8	2.4	2	3.2	2.14	2	1.4	2.5	1.1	2.2	2.5
Q	2.1	3.5	2.5	3	2.49	1.8	2.3	2	2.6	2	3.2
R	2.7	2.8	2.5	3.5	2.97	3	3.2	3.5	2.2	2.5	3.5
S	4.9	5.7	4.5	4.4	4.87	4.5	4.5	5.5	5.5	4.2	5.4
T	6	7	6.5	5.5	6.17	5.5	6.2	6.5	6	5.3	6.7
U	7.5	8	7.2	6.5	6.99	6	6.25	8	6.5	6.5	6.9

Calculations

From the raw data set analysis, firstly the measured error was compared to the true error using a scatter graph. Furthermore, the error of the measured defect size was also assessed by visualisation with guidelines of $\pm 0.5mm$ and $\pm 1mm$, which was done by extracting the equation of the trendline for measured defect size and adding and subtracting to the y-intercept. These graphs can be found in full in appendices A and B.

Then, the error for each measurement was taken by calculating the difference between the measured result and the known defect size. The mean and absolute mean of this error data was calculated, by using the $= AVERAGE()$ excel function with and without the $= ABS()$ function. From these values, the confidence interval for the true and absolute mean were also calculated by the following method:

$$\text{Standard Deviation} = STDEV.S(x)$$

$$\text{Standard Error} = \frac{\text{Standard Deviation}}{SQRT(COUNT(x))}$$

$$\text{Error Margin} = 1.96 * \text{Standard Error}$$

$$\text{Confidence Limits} = \text{Mean Error} \pm \text{Error Margin}$$

$$\text{Confidence Interval} = \text{Confidence Upper Limit} - \text{Confidence Lower Limit}$$

When calculating the error margin, a value of 1.96 was used to calculate a probability of detection of 95%. This is the standard for critical inspections, whereas for more regularly carried out, non-critical inspections a POD of 50% may be more acceptable (Health and Safety Executive, 2003).

Results and Discussion

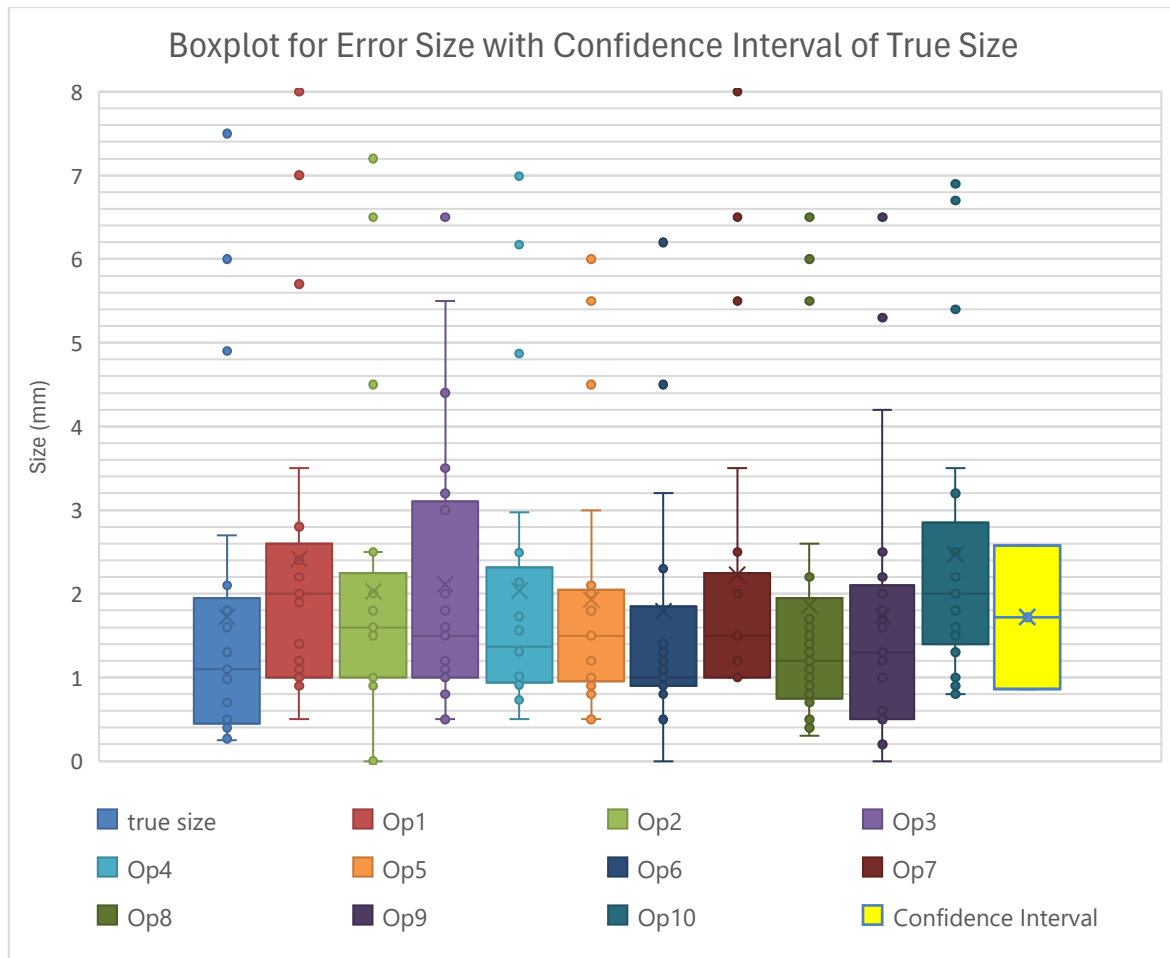


Figure 1 - Boxplot for error size, with comparison to the confidence interval for true size

The above boxplot shows the distribution of values measured by each operator, compared to the true size of each and the confidence interval of the true data. This visualisation allows for easy comparison of mean values and overall reported measurements, as well as a comparison to the confidence interval for true size, and is carried out as standard POD data analysis in research surrounding the method (Burrowes, Ginzel, Pereira, & Tavares, 2023).

One can see that each operator generally overestimates defect size; the mean and IQR for each operator is greater than that of the true size dataset. However, each is also within the true size confidence interval, with some being closer than others to the centre. Furthermore, one can also see that operators 2, 6, and 9 missed one or more defects, as denoted by them reporting a size of 0mm. Operators 4 and 8 show to be overestimating defect size less than the others, with tighter IQRs and the lowest means. This is corroborated in the error bar chart below, which shows these two to have the lowest absolute mean error values, at 0.371 and 0.375 respectively.

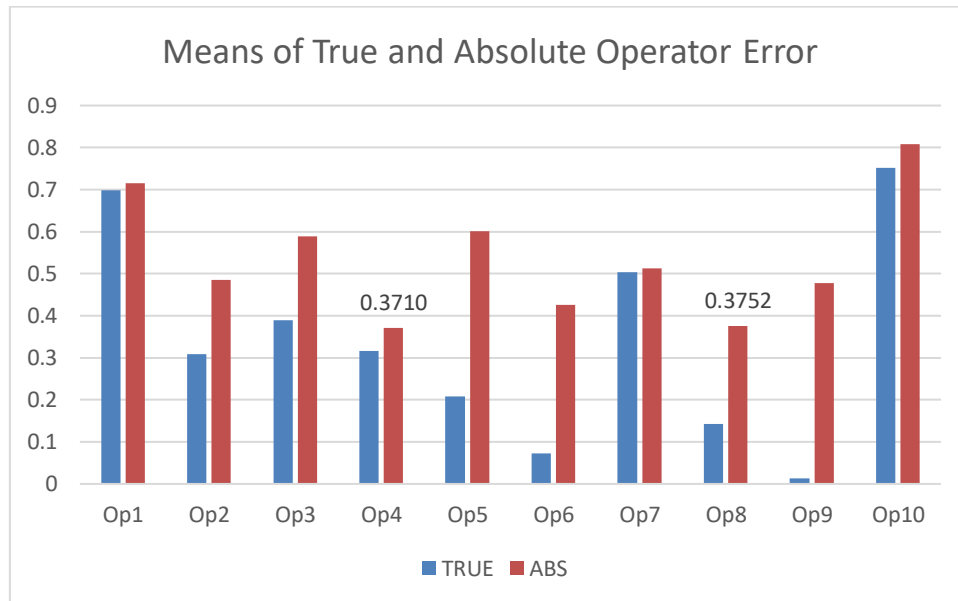


Figure 2 - Graph for mean error and absolute error in each operator across each defect

Comparing the general overall accuracy of each operator in their estimation of defect size, the first conclusion that can be made is that measurement of the absolute data is important, as it exposes where the true mean error can be misleading. This can be seen particularly with operator 9, where the mean true error is almost zero, at $0.0133mm$, however the mean absolute error is significantly higher at $0.4781mm$. This suggests operator 9 over and underestimated the true defect size somewhat equally, resulting in a low mean error despite the operator significantly misjudging defect size in reality. This can be confirmed in the true line comparison graph for Op9, where one can see measured values both significantly above and below the true line.

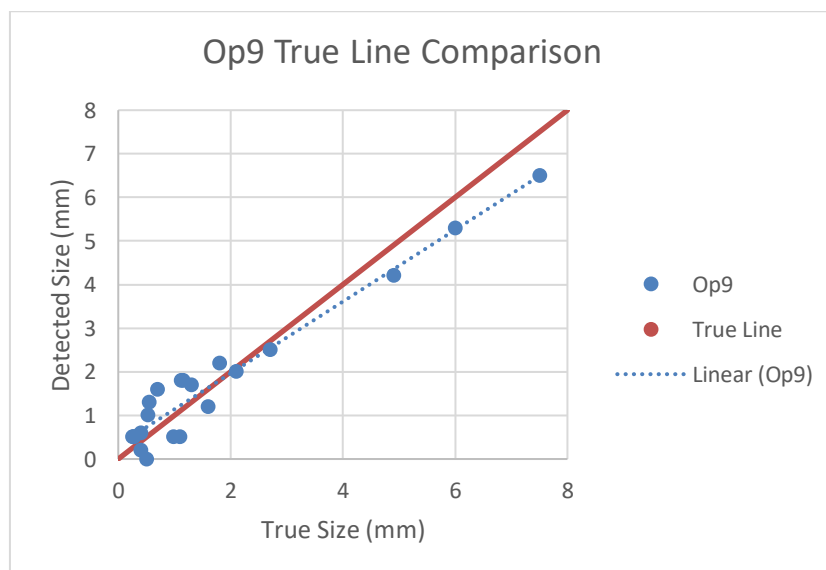


Figure 3 - Op9 True Line Comparison

One can also see from Figure 2 - Graph for mean error and absolute error in each operator across each defect that the majority of error came from operators overestimating error size, due to the true error value being in many cases close to the value for absolute error. This was calculated and is shown more clearly below.

Table 2 - Table showing nature of error for each entry

	Op1	Op2	Op3	Op4	Op5	Op6	Op7	Op8	Op9	Op10	Total
Overestimated	19	14	17	18	15	13	20	14	11	20	161
Underestimated	2	4	4	3	6	7	1	5	9	1	47
Missed	0	3	0	0	0	1	0	0	1	0	5
Correct	0	0	0	0	0	0	0	2	0	0	2

It can be seen that of the 210 entries, 161 were overestimates, 47 were underestimates, 5 defects were missed entirely and only 2 were measured exactly correct, to two decimal places. Given that this pattern exists across all operators, this indicates that the equipment or procedure itself has an increased probability of overestimating defect size to some degree. With that being said, it is clear from the boxplot alone, although is most clear in the true line comparison analysis in Appendix A, that each operator of course has different tendencies in the errors they have detected. Only 5 defects were missed, 3 of which all by operator 2, and only 2 were detected with accuracy to two decimal places, and these both by operator 8. This is indicative of no inherent tendency within the procedure or equipment to completely miss or perfectly predict defects.

Comparing operators 4 and 8, the absolute error values are close, and the boxplots also appear similar. In order to further ascertain accuracy, the true line and trendline comparisons can be examined.

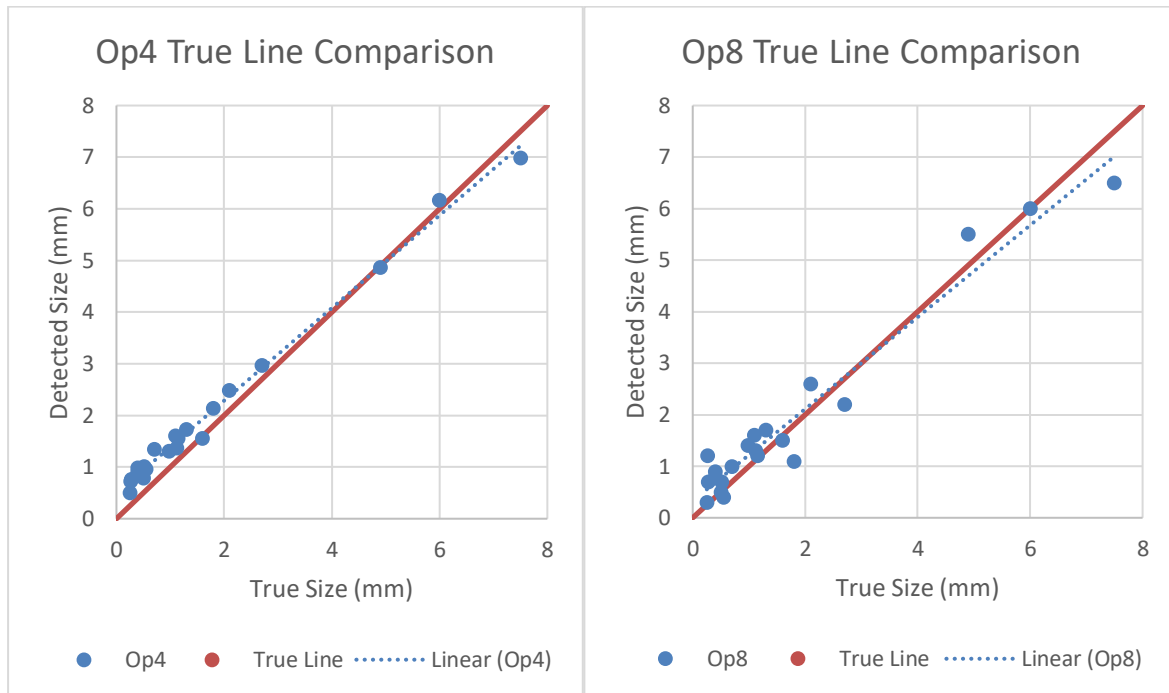


Figure 4 (Left) – Op4 True Line Comparison

Figure 5 (Right) – Op8 True Line Comparison

From these graphs, it is possible to see that Op4 consistently slightly overestimates defect size, with only the largest defect being underestimated. In contrast, Op8 more evenly over and underestimates defect sizing, which is also shown in the true and absolute mean error comparison in Figure 2 - Graph for mean error and absolute error in each operator across each defect, where the mean true error is shown to be significantly smaller than for Op4. However, Op8 also appears to mischaracterise defect size to a greater magnitude, which is a greater source of inaccuracy. This variance can also be studied with relation to the trendline, as is usually done in industry (Schneider & Rudlin, 2003) by comparing values for R^2 (Rentala, Mylavarapu, & Guatam, 2018). This analysis can be seen below.

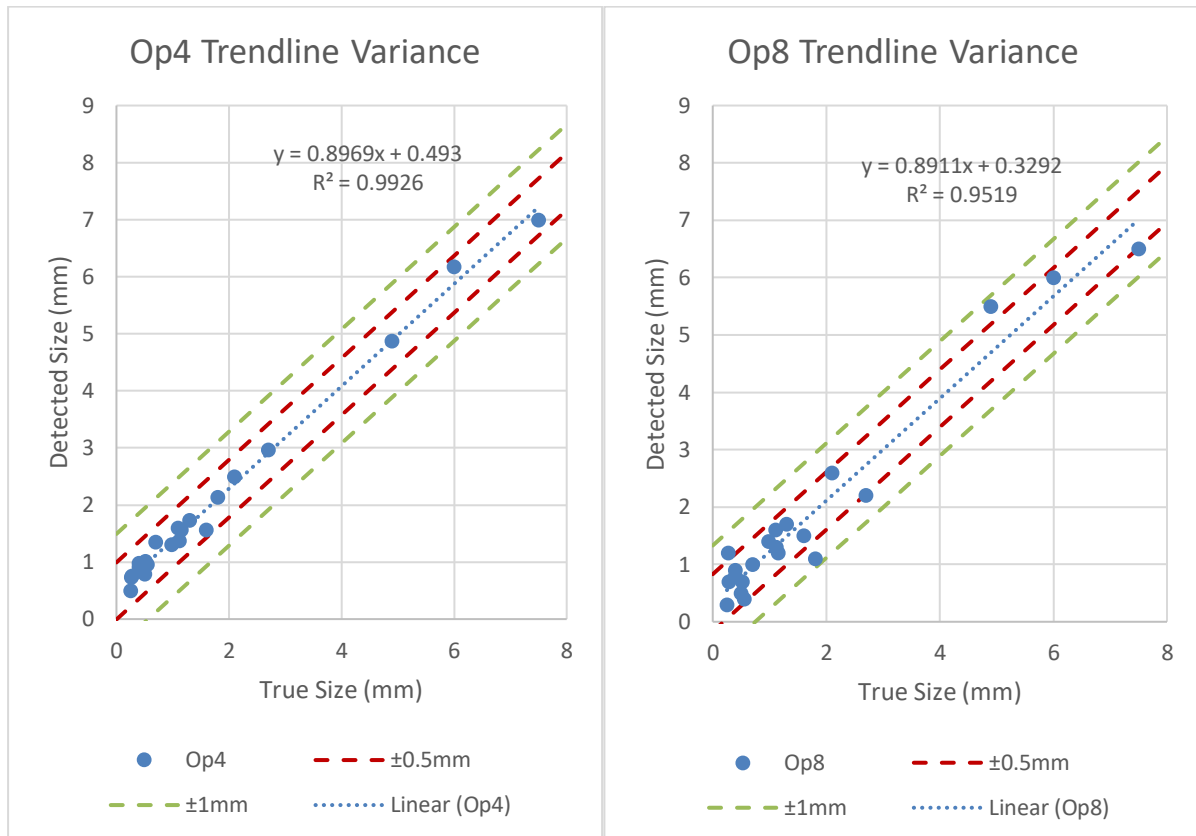


Figure 6 (Left) – Op4 Trendline Variance Comparison

Figure 7 (Right) – Op8 Trendline Variance Comparison

From the trendline variance, it can be clearly seen that the Op4 data is more consistent and linear than Op8, with no values being further than 0.5mm from the linear trendline. In contrast, for Op8 several values at both smaller and larger sizes are further than 0.5mm from the trendline. This can also be seen in the R^2 value for each trendline, with the R^2 value for technician 4 being 0.9926 compared to technician 8 with 0.9519. Therefore, Op4 appears to identify defect size with more consistency than Op8. The only other technician with an R^2 value of greater than 0.65 is Op7 with 0.9839, however Op7 has a high mean error and appears to detect errors with a hard minimum of 1mm, uniquely to all other technicians.

Therefore, given that Op4 has the lowest mean absolute error and the highest R^2 value, operator 4 appears to have gathered the most accurate results, while their tendency to overestimate defect size can be attributed to the nature of the experiment given it is present in all but one operator's data.

Conclusion

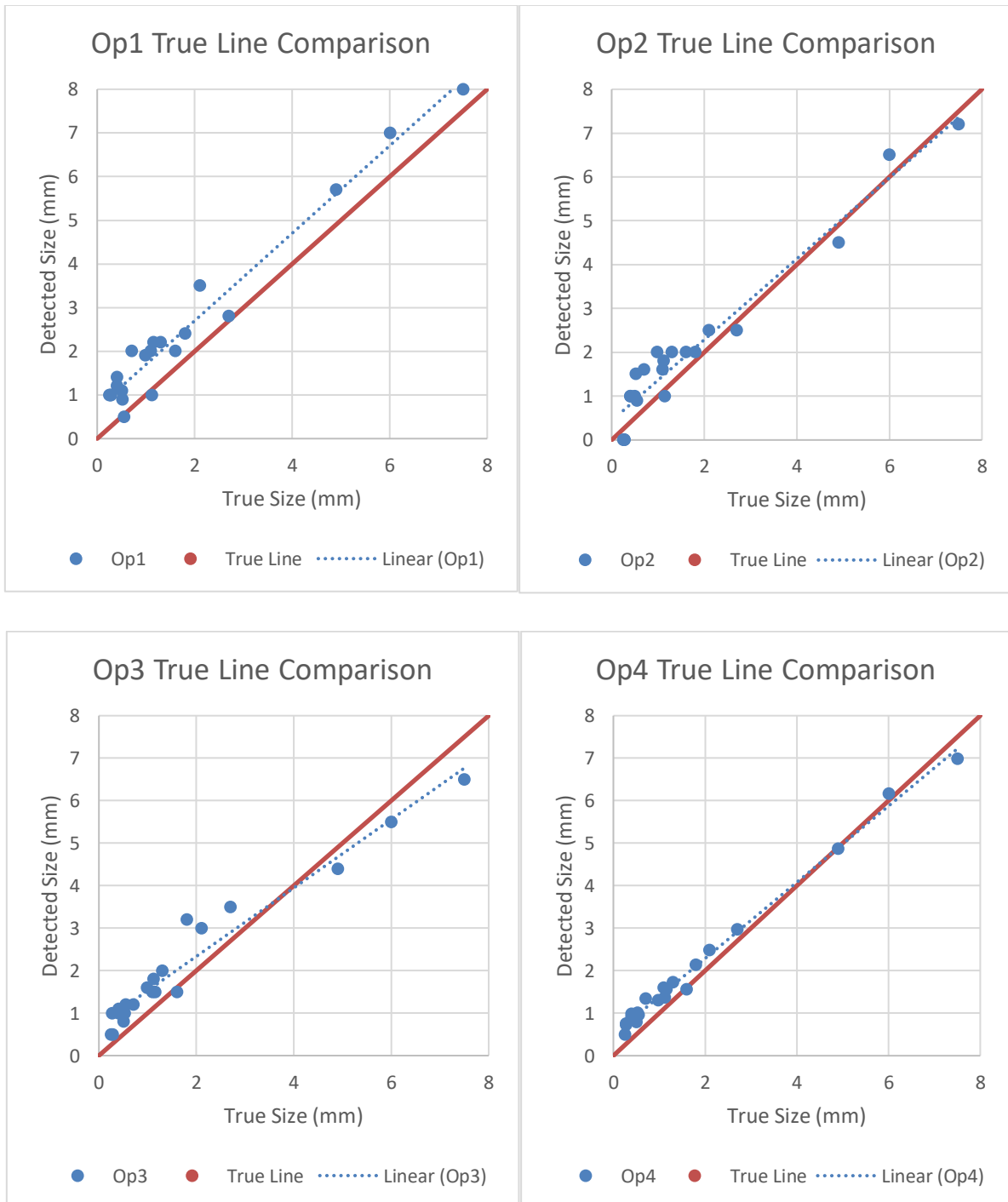
In conclusion, a statistical analysis of the given dataset was carried out including linear regression analysis according to the common analysis techniques used for POD datasets in industry. A boxplot was created and used as an overview comparison between each technician's data. The mean and mean absolute values were also taken and compared, and it was found that taking the absolute data was insightful as it gave an insight into the misleading effect of negative error on the true mean. From these analyses it was found that technicians 4 and 8 were generally most accurate. Furthermore, a linear regression was carried out on each technician's data, and this was compared to the true line and by changing the y-intercept of the line to compare error magnitude. This served to better display magnitude of error for individual measurements, as well as show trends towards over or underestimation of data. Also, to this end, the number of entries that over or underestimated defect size were calculated and shown. This showed a general tendency across the study to overestimate defect size, and it was concluded that this was likely due to the nature of the equipment or procedure rather than due to human error. These visualisations also showed that technician 8 detected size with a less consistent trend than technician 4, as well as with the greatest proportion of underestimations of the dataset. Thus, technician 4 was found to be the most accurate.

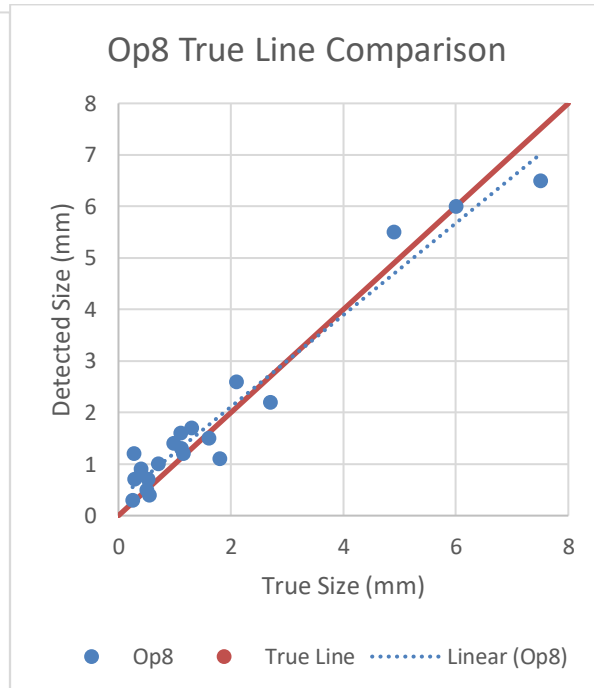
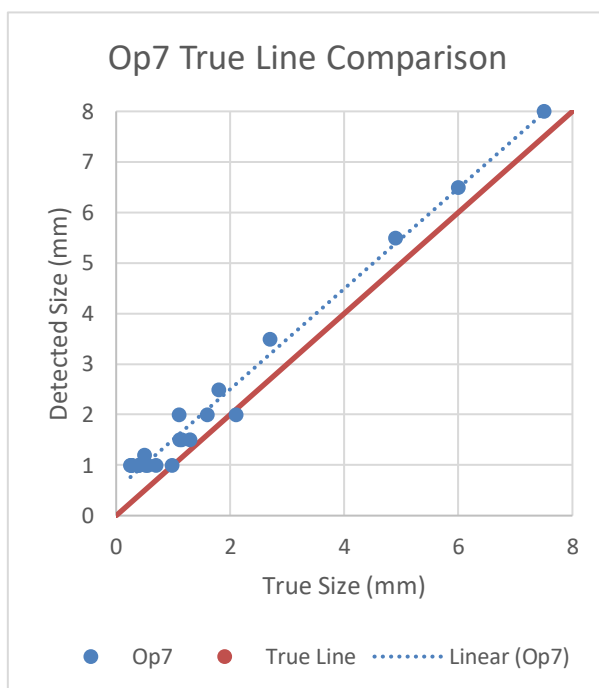
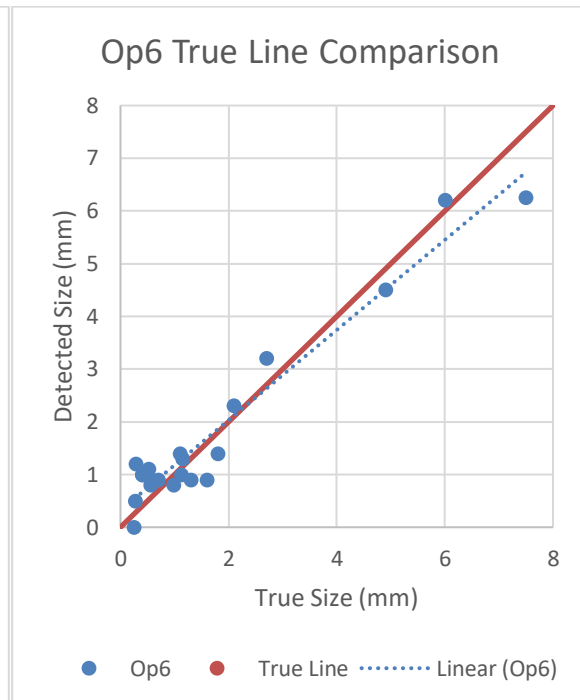
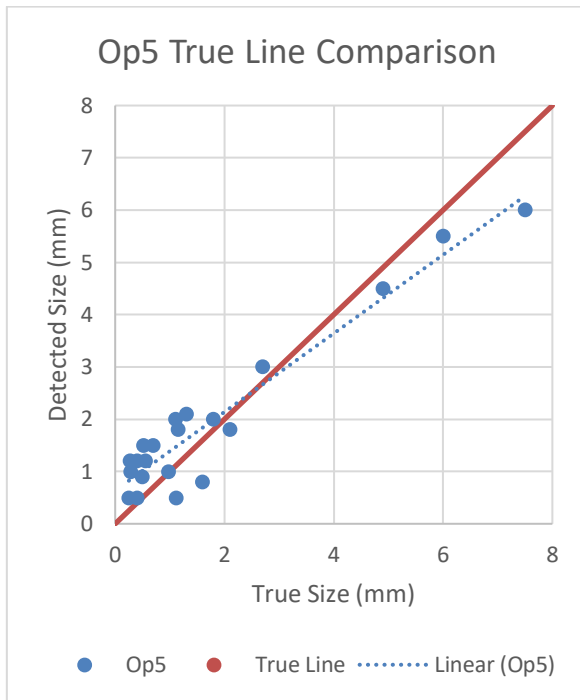
References

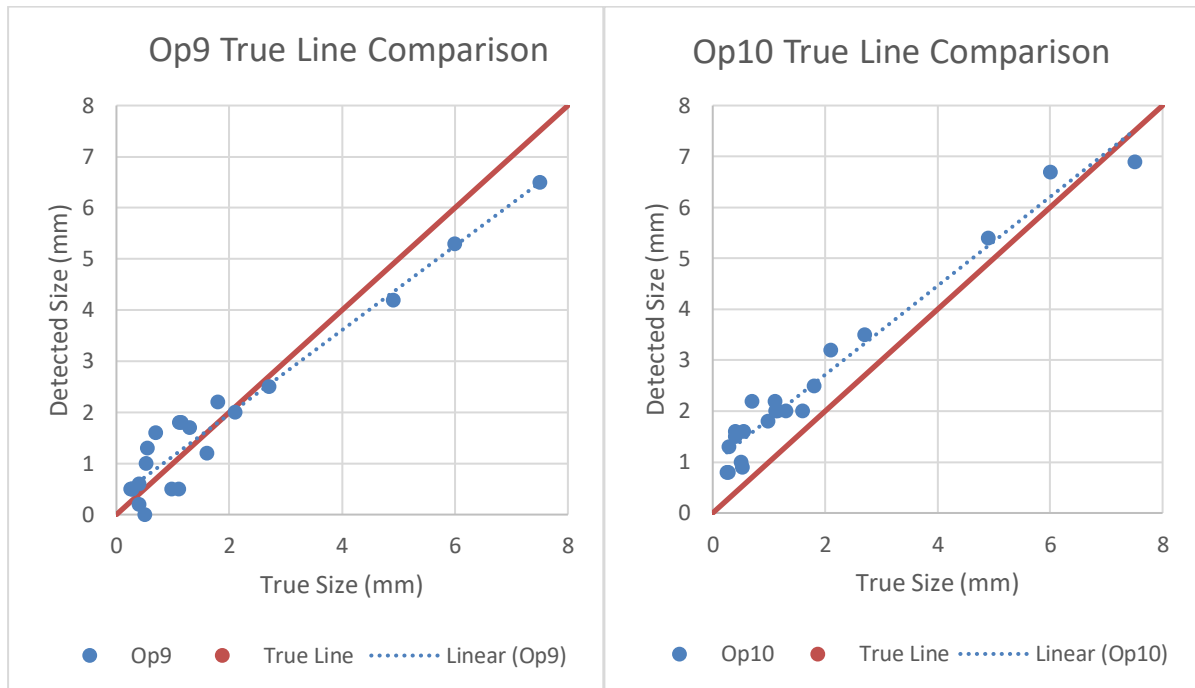
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Appendices

Appendix A: True Line Comparisons







Appendix B: Trendline Variance Comparisons

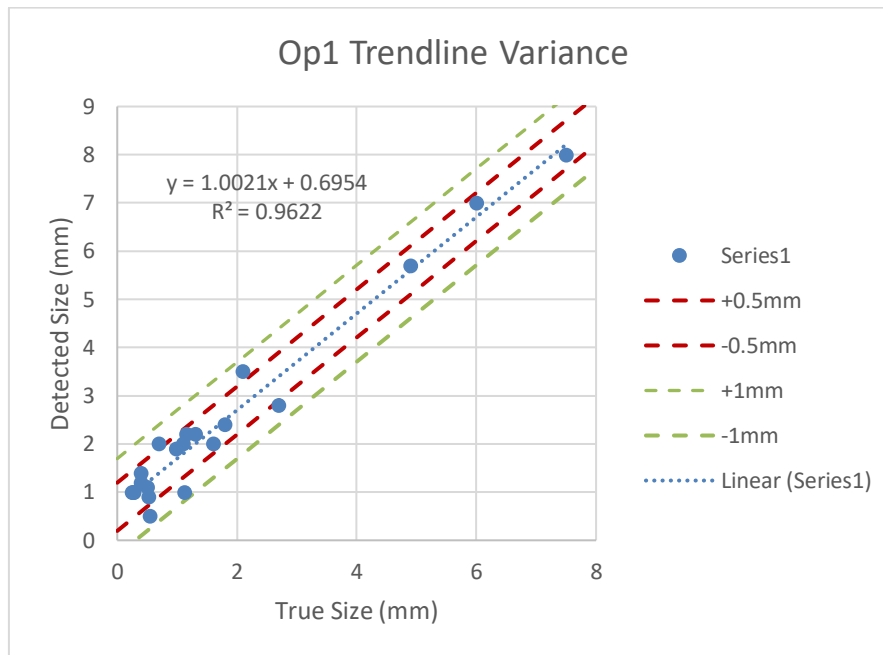


Figure 8 - Op1 Trendline Variance

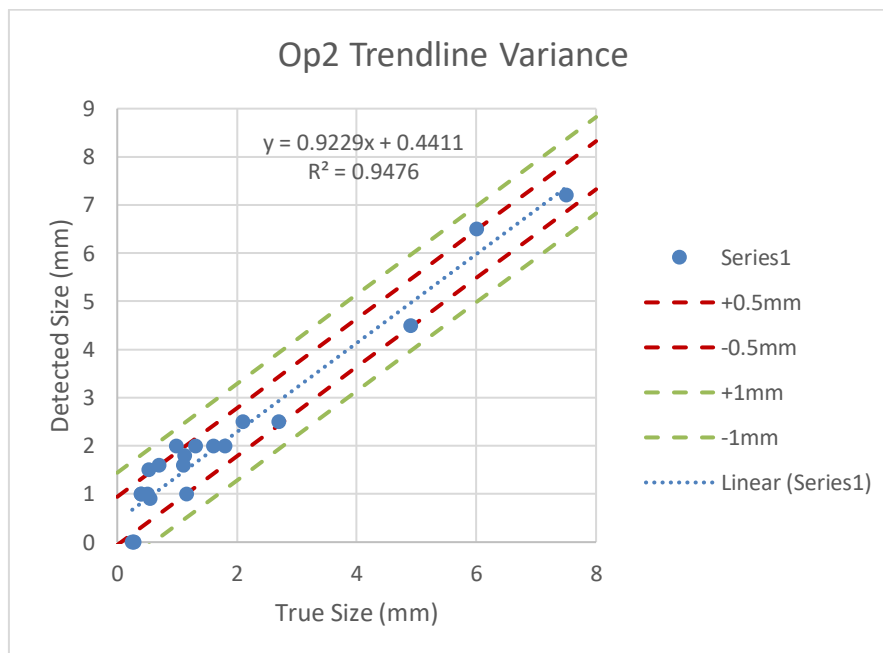


Figure 9 - Op2 Trendline Variance

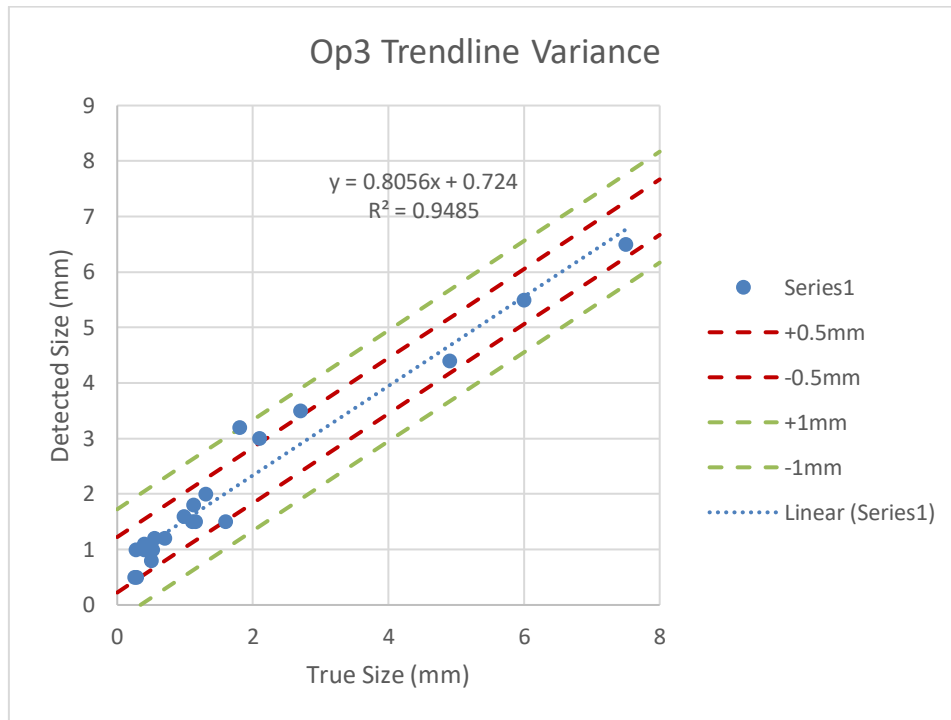


Figure 10 - Op3 Trendline Variance

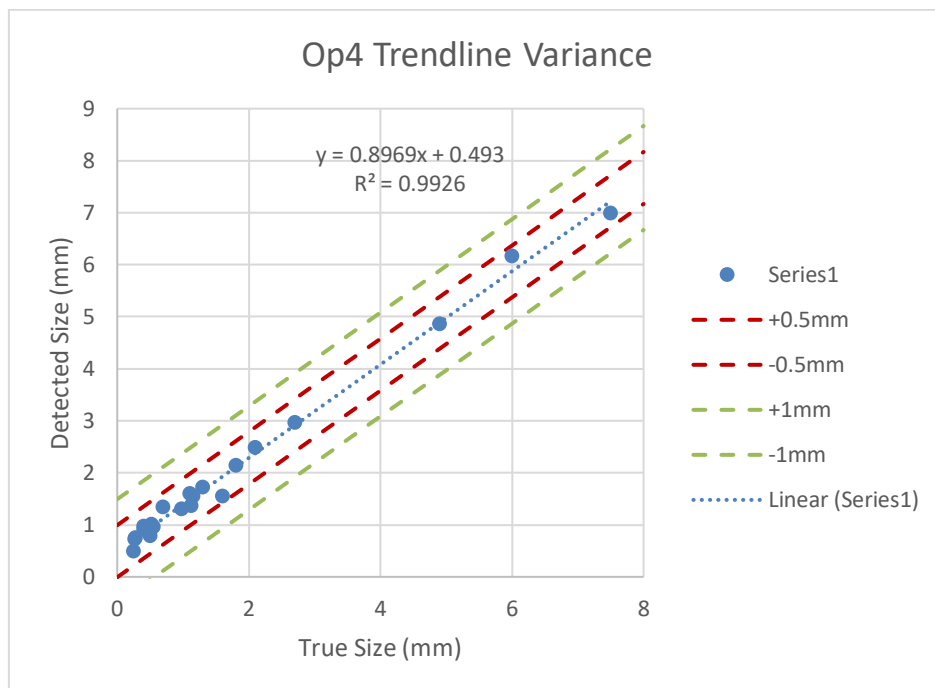


Figure 11 – Op4 Trendline Variance

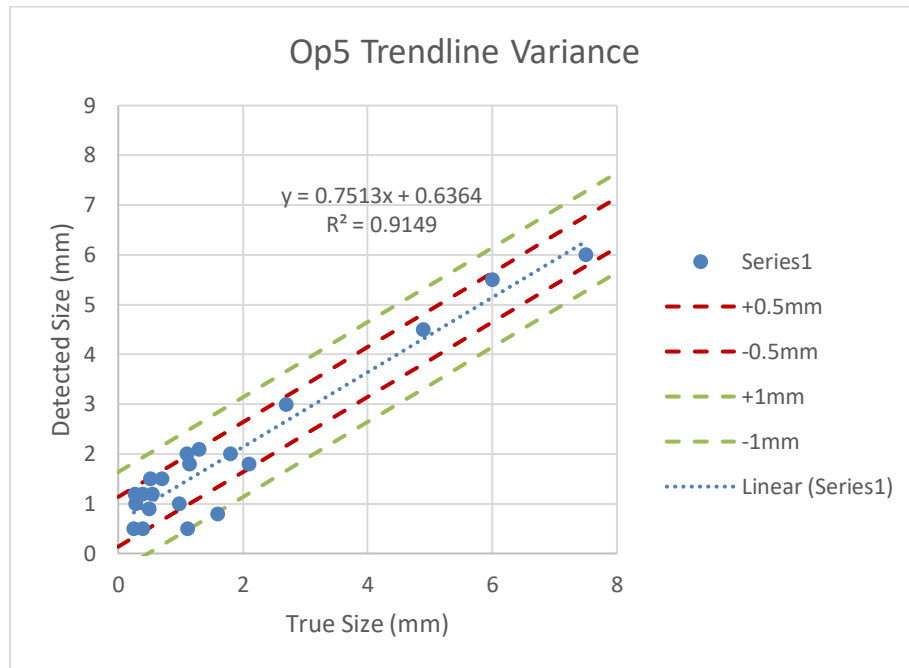


Figure 12 - Op5 Trendline Variance

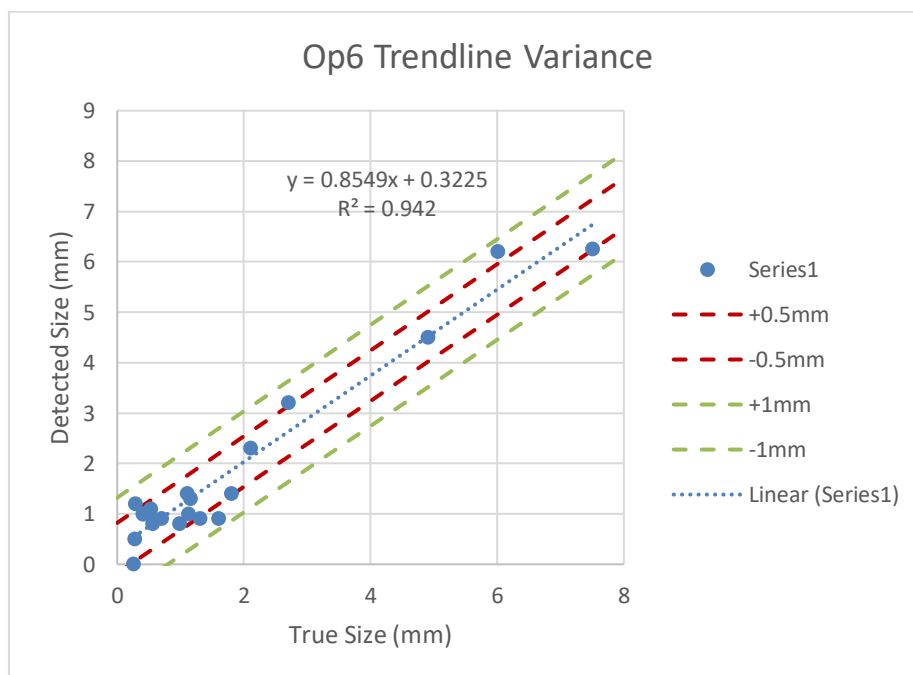


Figure 13 - Op6 Trendline Variance

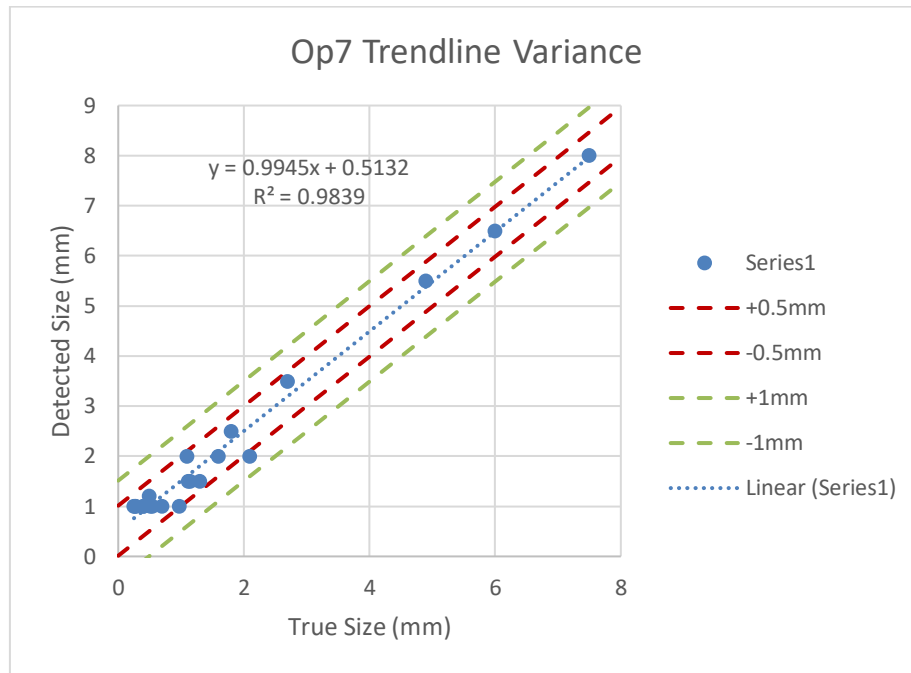


Figure 14 - Op7 Trendline Variance

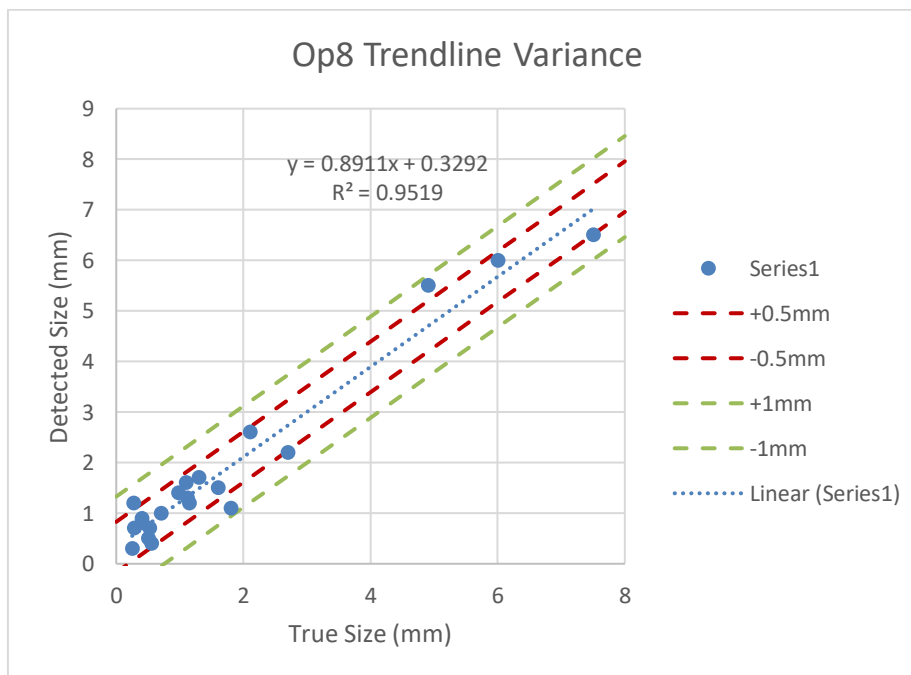


Figure 15 – Op8 Trendline Variance

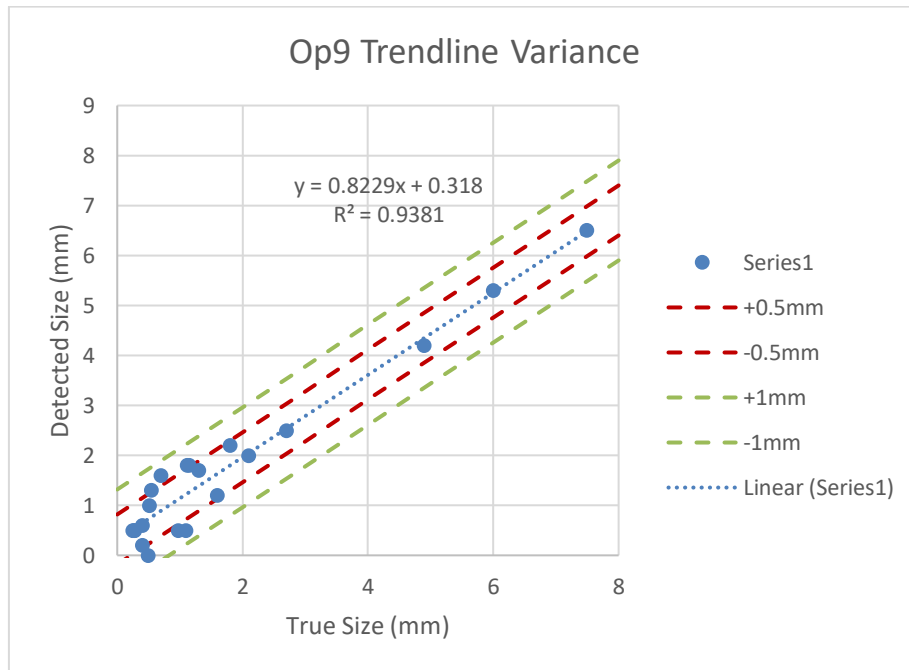


Figure 16 – Op9 Trendline Variance

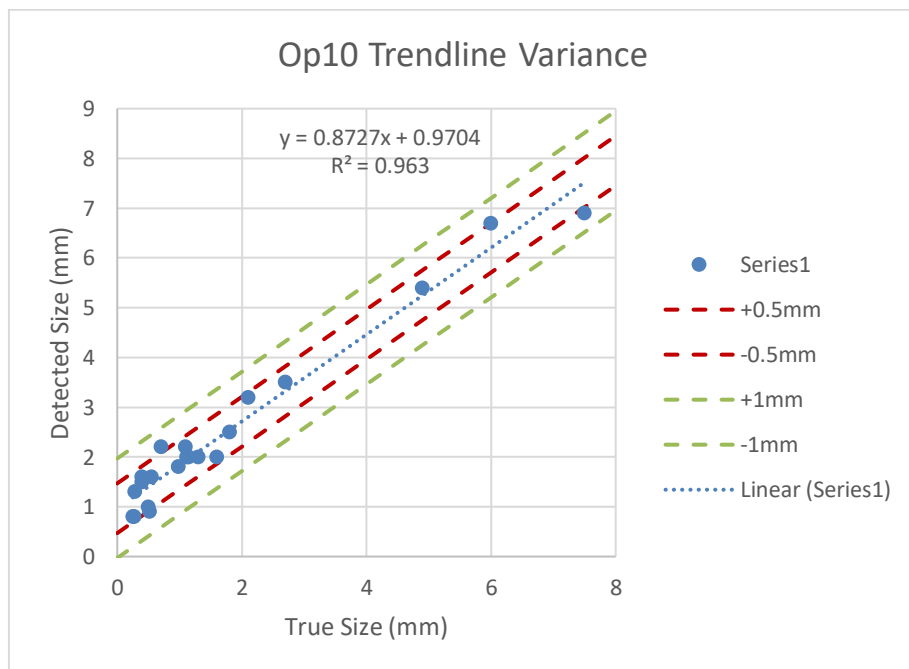


Figure 17 – Op10 Trendline Variance

MSc Motorsport Engineering

Ultrasonic Attenuation Coefficient Determination

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Abstract

A mild steel cuboid block and a brake disc were tested using an ultrasonic flaw detector and a 5MHz probe and on both samples a series of time of flight measurements were taken. The FSH% (full screen height percentage) of the three echoes of the back wall of the sample were taken and from this data, the attenuation coefficients were calculated for each echo. Analysis of this data was carried out including calculating an average value with a 95% confidence interval, as well as a frequency analysis on each calculated dataset. The attenuation coefficient values calculated were -0.1495 for the steel block and -0.501 for the brake disc, with confidence intervals of -0.0119 and -0.055 respectively, showing greater accuracy for the steel block due to an increased number of measurements and a smoother surface.

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Apparatus

- Ultrasonic, zero-degree 5MHz probe.
- Ultrasonic flaw detector



Figure 18 - Ultrasonic Flaw Detector

- Used brake disc



Figure 19 - Brake disc

- Cuboid mild steel block



Figure 20 - Steel block

- Water
- Vernier

Procedure

Introduction

The purpose of this experiment is to determine an attenuation coefficient for each of the samples. This will be accomplished by a calculation based on measuring the time of flight of the ultrasonic beam through the sample. Multiple measurements will be made, and this data will be analysed as part of the determination of these coefficients.

Method

Firstly, the samples were measured with the vernier to determine the thickness of the surface that would be measured, thus giving the distance the UT wave travels, which is needed to calculate attenuation coefficient. Water was then applied to the sample before measurement began, which serves as a medium between the probe and the material to ensure the sound energy is properly transmitted into the specimen (NDE-Ed, n.d.).

10 measurements were taken at different positions on each of the square sides of the steel block sample. The height percentage on the display was taken for three echoes at each location, and to do this the range on the display was adjusted to show the three echoes. An example of this is shown below.

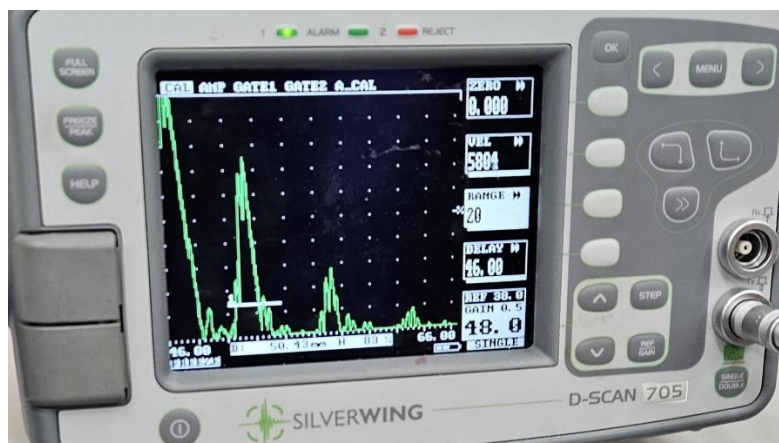


Figure 21 – The UT flaw detector showing three echoes of the back wall of the steel block during measurement

The velocity was also changed in order to match the distance shown on the display to what was measured with the vernier, which, at the first echo, is doubled, due to the wave travelling to and from the back wall of the sample. These results were recorded in Excel for later processing.

The same was attempted to measure the steel block lengthways, however H% results were not taken for this due to the nature of the result. This is further discussed in the results.

The same was also carried out for the brake disc sample, for which readings at 6 locations were taken, taking care to ensure that the sensor was positioned on the front friction face such that it was not directly above the material that connects the front and rear faces of the vented disc together. This ensured that the measurements were accurate to the measured thickness of material.

Measurements

Table 4 – H% Values for the steel block

Steel Block H%			
Measurement	Echo 1	Echo 2	Echo 3
1	85	39	21
2	74	35	20
3	77	39	23
4	94	47	25
5	94	46	25
6	86	42	25
7	80	39	22
8	76	35	21
9	84	40	22
10	76	35	21
Mean	82.6	39.7	22.5
1	74	37	18
2	68	29	17
3	70	31	17
4	68	32	20
5	74	34	22
6	70	30	17
7	74	37	25
8	59	28	16
9	71	31	16
10	74	35	22
Mean	70.2	32.4	19

Table 3 – H% Values for the Brake Disc

Brake Disc H%			
Measurement	Echo 1	Echo 2	Echo 3
1	92	51	23
2	84	39	21
3	85	38	17
4	88	49	25
5	82	43	22
6	84	47	21
Mean	85.83333	44.5	21.5

Table 5 – Measured thickness for each sample

Thickness (mm)	
Steel block square side	19
Steel block long side	80.5
Brake disc friction surface	6

Calculations

Attenuation Coefficients

By comparing the height of each echo on the UT display, and using the measured thickness of the sample, the attenuation coefficient can be calculated using the following equation (NDE-Ed, n.d.):

$$A = A_0 e^{-\alpha z}$$

This can be rearranged for the attenuation coefficient α :

$$\alpha = \frac{20 \times \log\left(\frac{A}{A_0}\right)}{z}$$

In excel, this can be expressed as:

$$= (20 * LOG(A/A_0))/(z)$$

The z value depends on the echo being calculated, with the attenuation coefficient of echoes 1-2 and 2-3 is $2 \times thickness$, and for echo 1-3, $4 \times thickness$ is used. This is because z represents the distance travelled by the UT wave, so for echoes 1-2 and 2-3 the wave travels to the back wall and back to the sensor, however for echo 1-3 this journey occurs twice. Ultrasonic attenuation is mainly caused by the UT wave scattering due to reflections off grain boundaries within a metal, as well as absorption and beam spread that result in lost energy (Holloway, 2017).

The mean values for each echo were then calculated, using the $= AVERAGE()$ excel function.

Frequency Analysis

Next, a frequency analysis was carried out on each set of coefficients. Therefore, in order to determine the intervals, the minimum and maximum value of the dataset was taken using the $= MIN()$ and $= MAX()$ excel functions. Based on this, the minimum was taken to be -0.22 and maximum -0.06 for the steel block, and -0.66 and -0.38 for the brake disc. For the steel block, the step size was 0.02 , and for the brake disc the step size was 0.06 .

The frequency was taken by using the $=COUNTIFS()$ function, to count how many values within the set fit within a given range, an example of which is below.

$$= COUNTIFS(dataset, ">-0.22", dataset, "<-0.20")$$

This was done for all ranges and graphed against the midpoint of each range, and finally the mean and confidence interval for the dataset was also calculated and added to the graph.

Results and Discussion

Steel Block

Square Sides

The attenuation coefficients were calculated for each echo as detailed above, and the averages are shown in the graph below.

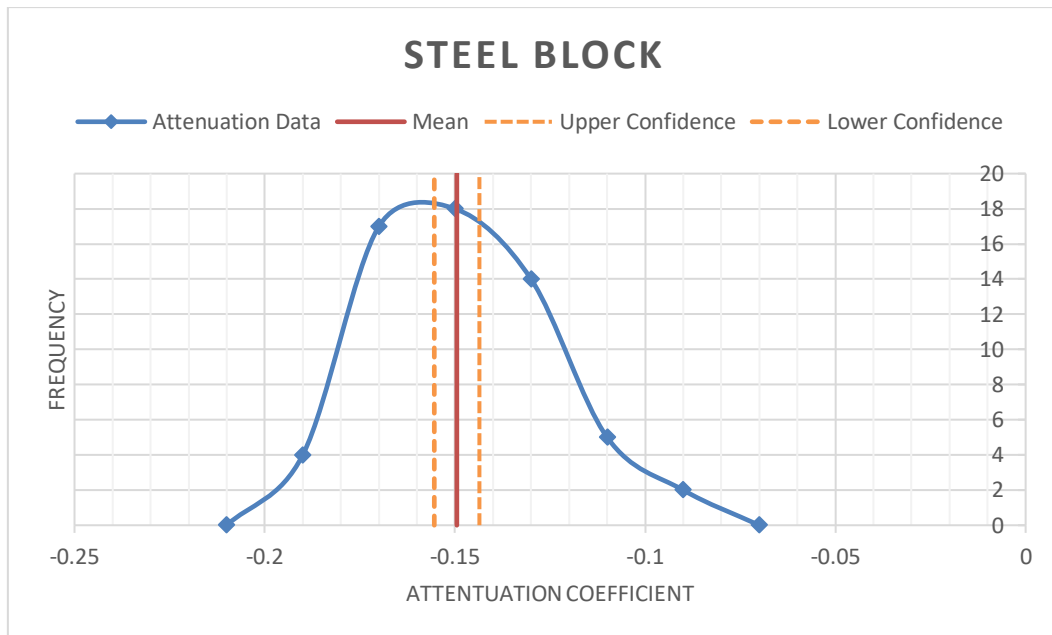


Figure 22 - Frequency analysis for attenuation coefficient of the steel block

The distribution of attenuation coefficients obtained for the steel block shows a recognisable bell curve, with a mean value of -0.1486 for one of the square sides, and -0.1494 for the other, with an overall mean of -0.1495 . This confidence interval was determined to be -0.0119 . The bell curve shape shows that the calculated values have variance but tend towards an average value, which gives credence to the accuracy of the experiment given a bell curve is the expected result for a frequency analysis of this kind. The variance can be generated by differences in surface smoothness causing interference, or differences within the material like the metal's grain structure, where grain boundaries can disrupt the wave's travel (NDE-Ed, n.d.).

Long Side

Measurement of the block lengthways, at a thickness of 80.5mm , was also attempted, and the monitor output for this measurement can be seen below.

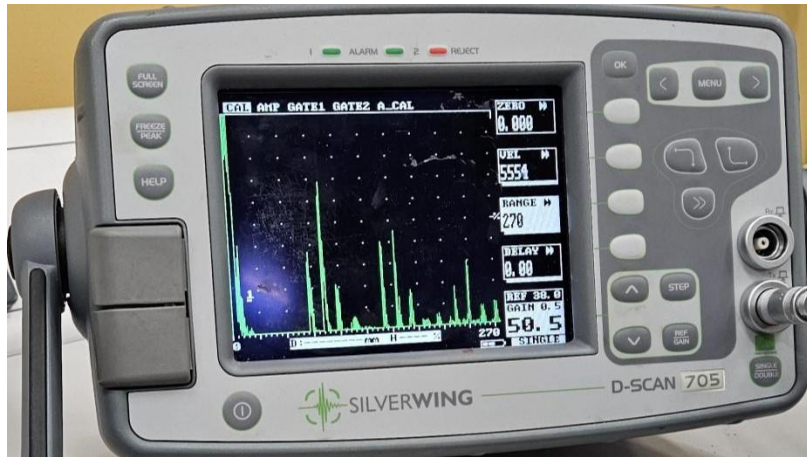


Figure 23 - The UT flaw detector output for the steel block measure lengthways

The results show four peaks echoing three times on the display. These four peaks are caused by internal reflections, which occur due to beam spread and to the long, narrow nature of the geometry in the test meaning that there are reflections off of the material boundary. In order to circumvent these issues, a narrower beam can be used. This can be achieved with a differently sized transducer (Holloway, 2017). Alternatively, when inspecting close to the material boundary such as in this case, a reference standard with the reference discontinuity located at the boundary can be used (USAF, 2010).

Brake Disc

The brake disc frequency analysis can be seen below.

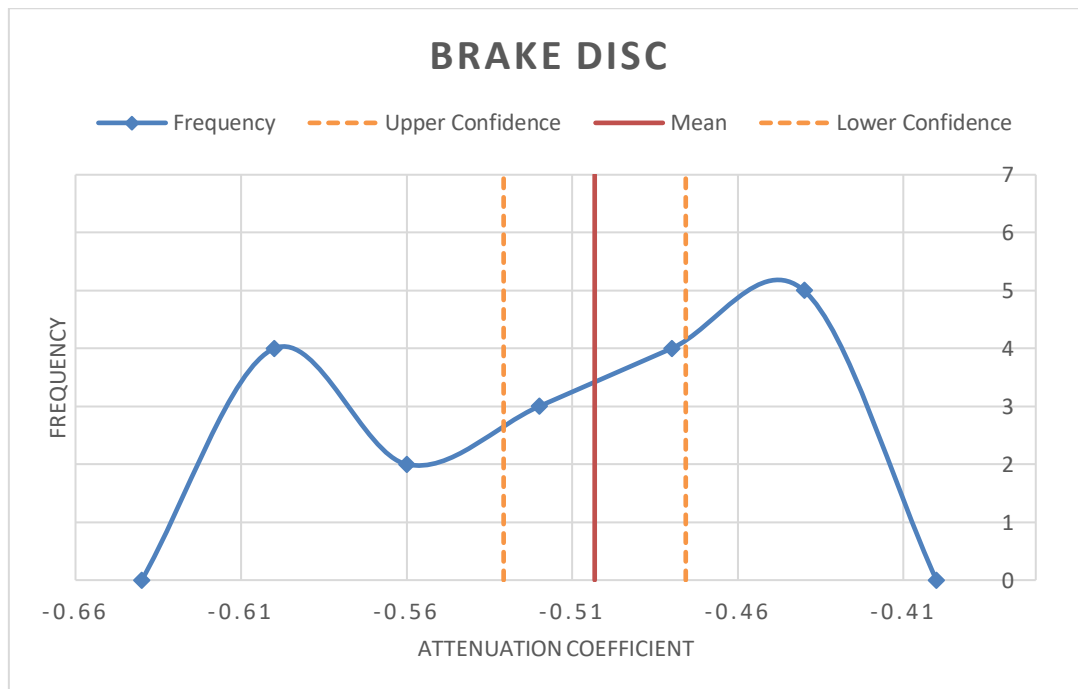


Figure 24 - Frequency analysis for attenuation coefficient of the brake disc

This analysis produced a curve which does not resemble a typical bell curve to the same degree that the steel block does, which could be due to a number of reasons. One is that less measurements were made for the brake disc. For the steel block, 10 measurements were made for each square side, and so 60 attenuation coefficients were averaged into the frequency analysis. For the brake disc, only 6 measurements were made, being 18 coefficients averaged out. One would reasonably expect greater inaccuracy due to this (British Standards Institution, 2011).

Furthermore, when measuring the brake disc with the UT flaw detector, a significant amount of noise was detected in the nearfield range. This is due to significant surface imperfections and grooves made by the friction of the brake pad rubbing on the brake disc when in use, which can significantly influence the results of the UT technique and render the results inaccurate (Abdelhay & Mubark, 2004). When the UT wave encounters this roughness, it causes increased scattering, and as this occurs at the surface of the material, it is within the nearfield range. This is a range of increased inaccuracy due to significant interference from incoming and outgoing waves, which obscures flaws and makes them difficult to detect and analyse in this area (NDE-Ed, n.d.). This phenomenon can be seen in the readout acquired from the experiment, shown below.

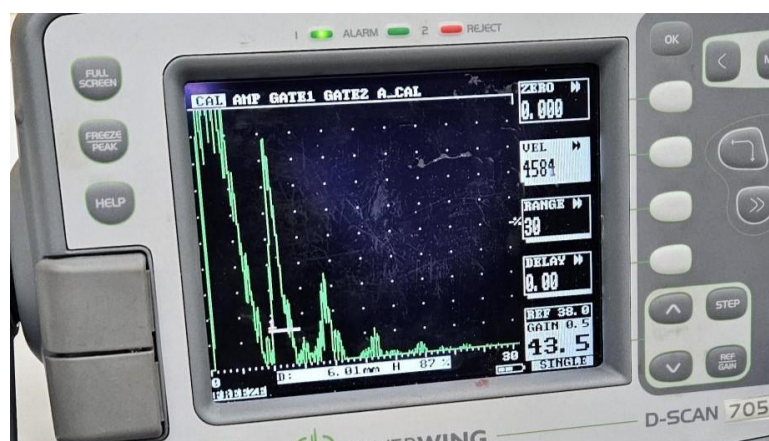


Figure 25 - Ultrasonic readout for the brake disc, showing significant noise in the nearfield range

In the industry, it is common to use a wedge to take the surface of the material outside of the nearfield range, which increases the accuracy of the measurement. This required further calibration and so was not carried out in the experiment but would look similar to the below photo captured during the experiment.



Figure 26 - UT Probe with a block affixed

The mean value was calculated to be -0.501 , with a confidence interval of -0.055 . The confidence interval is wider than that of the steel block, which is because the data has greater variance due to the aforementioned inaccuracies.

Conclusion

In conclusion, an experiment was carried out on the two given samples in order to determine material attenuation coefficients for each. For both samples, a series of time of flight measurements were taken using a UT flaw detector and a 5MHz probe. The attenuation coefficients were calculated for each echo, and the results were analysed. This included calculating an average value with a 95% confidence interval, as well as a frequency analysis on each calculated dataset. The attenuation coefficient values calculated were -0.1495 for the steel block and -0.501 for the brake disc, with confidence intervals of -0.0119 and -0.055 respectively, showing greater accuracy for the steel block due to an increased number of measurements and a smoother surface.

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