

Ultrasonic Attenuation Coefficient Determination and Probability of Sizing Analysis

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Abstract – This report is split into two parts. The first part is analysing the determination of Ultrasonic Attenuation Coefficient (Ratio dB/mm) in two different samples, a mild steel rectangular block and an automotive disc brake. The second part is investigating defect measurement accuracy from ten different operators using statistical analysis such as linear regression and normal distributions.

The Ratio dB/mm was calculated as -0.102dB/mm and -0.471dB/mm for the mild steel block and disc brake respectively, difference in the results were found to be from material property differences (density) and thickness of the samples.

For Part 2, linear regression suggested operator 9 was the most accurate and operator 2 was the least accurate, whilst with the normal distributions, operators 3 and 9 were the most accurate. However, operators 4 and 7 were found to be the least accurate.

Part 1: Ultrasonic Attenuation Coefficient Determination

1. Apparatus

- Ultrasonic Flaw Detector
- Ultrasonic, zero-degree, 5MHz Probe
- Ultrasonic Imaging Gel
- Measuring Callipers

2. Introduction

Ultrasonic flaw detection is a vital method to material analysis as it allows for defect and attenuation coefficient determination whilst being non-destructive to the material sample. This allows the application to be used in real time on physical components to assess the structural condition where the assembly can be left together or refitted after the analysis. Defects within the material which cannot be seen on the surface using visual or microscopic techniques are

able to be identified; highly important as these can frequently have the largest effect on a materials strength.

The attenuation coefficient represents how easily a material can be penetrated by a sound wave. Differences in this value across a sample could indicate a difference in density, potentially related air gaps (defects) within the microstructure (Deng, 2019).

During this report the attenuation of coefficient of two materials samples will be calculated and the accuracy of the determination will be compared. The two samples will be a mild steel rectangular block and a standard solid disc brake of a car. The equipment used will be an ultrasonic, zero-degree 5MHz probe and an ultrasonic flaw detector and A-Scan will be displayed.

In an A-Scan the ultrasonic amplitude is plotted against time, normally resulting in 3 peaks (E1, E2 and E3). The distance between the peaks represents the thickness of the sample due to the delay in time as the waves travel through the material.

The detector records an E1, E2 and E3 reading which will be measured from five different locations from the same side on the sample. The average for each E value will be calculated giving us an idea of the variation in results between each location. The thickness of the sample will also be recorded and averaged, allowing the attenuation coefficient to be calculated.

The attenuation coefficient (ratio dB/mm) is given as $20/\text{distance} * \log(A2/A1)$. In this equation, $A2/A1$ can be changed to $A3/A2$ or $A3/A1$ where distance (d) = the length the sound travels. Two times the thickness of the material for $A2/A1$ and $A3/A2$, and four times the thickness for $A3/A1$. A1, A2 and A3 represent the E1, E2 and E3 values, therefore because of the delay between A1 and A3, the distance used is four times the true sample thickness.

This method provides a way of analysing materials properties and their porosities. Whilst in this report the investigation will be focused on metallic components, there have been several studies on other materials such as carbon fibre. Echo immersion reflection techniques were used with a 5MHz flat probe and calculated an attenuation coefficient of 1.60dB/mm with no voids. Then using linear and parabolic curves, they were able to calculate the coefficient with porosity between 0.03%-0.5% and 0.5%-4.96% respectively (LIN, LUO, TIAN, LI, & GUO, 2008).

3. Measurements and Graphs

Table 1 shows the measurements taken from the mild steel rectangular block using the ultrasonic probe and flaw detector. E1 E2 and E3 are the peaks produced by the probe and can be seen to decrease consistently at all positions.

Table 1: Mild Steel Block Measurements

Mild Steel Rectangular Block				
Pos	E1	E2	E3	Thickness (mm)
1	41	23	15	20
2	63	38	24	Gain
3	77	46	30	15
4	58	40	27	Frequency (MHz)
5	75	41	27	5
Average	62.8	37.6	24.6	

Table 2: Attenuation Coefficient for Mild Steel Block

Mild Steel Rectangular Block			
Ratio dB	A2/A1	A3/A2	A3/A1
1	-0.12552801	-0.09282	-0.10917
2	-0.10977848	-0.09979	-0.10478
3	-0.11186645	-0.09282	-0.10234
4	-0.080684	-0.08535	-0.08302
5	-0.1311387	-0.09071	-0.11092
Ave	-0.11179913	-0.0923	-0.10205

Now looking at Table 2 we can see the attenuation coefficient for the mild steel block that has been calculated and averaged out across the five locations. The average from A2/A1 to A3/A1 differs by only 0.0098 dB/mm, which indicates a relatively accurate set of measurements given the amount of data collected and equipment used.

Table 3: Brake Disc Measurements

Brake Disc						
pos	E1	E2	E3	Thickness (mm)	Gain	Frequency (Mhz)
1	97	24	7	12.6	28	5
2	99	24	7	12.65		
3	90	19	5	12.6		
4	80	17	5	12.61666667		
5	93	23	6			
Average	91.8	21.4	6			

Table 4: Brake Disc Attenuation Coefficient

Brake Disc Attenuation Coefficient			
Ratio dB	A2/A1	A3/A2	A3/A1
1	-0.48082	-0.42419	-0.45242
2	-0.48785	-0.42419	-0.45593
3	-0.53546	-0.4596	-0.49743
4	-0.53321	-0.42131	-0.47716
5	-0.48098	-0.46261	-0.4717
Ave	-0.50367	-0.43838	-0.47093

Table 3 and 4 shows the measurements and calculations gained from the brake disc which was analysed. This was done using the same method to the mild steel block. Similarly, the calculation for the Attenuation Coefficient were the same, providing an accurate comparison for two different materials.

4. Results and Discussion

Table 1 and 2 shows the results of the mild steel block under ultrasonic analysis to determine the attenuation coefficient for the material. Looking at Table 1 we can see the results collected. The averages for E1, E2 and E3 were 62.8, 37.6 and 24.6 respectively. This represents the sound level of the waves as they have been detected by the probe. The first peak (E1) is the interphase reflections, then E2 and E3 are the subsequent back wall echos, hence why the level decreases between E1 and E3 as the waves had been absorbed by the material through each pass (Gecko Robotics, 2021).

The results of the Attenuation Coefficient for the mild steel block are shown in Table 2 using the data from Table 1. A1/A2 and A1/A3 are two different ways of calculating the same answer and therefore a useful way of checking the accuracy of the calculations. In our results there is only a 0.0195 dB/mm variation which indicates accurate readings and calculations from the sample.

Table 3 and 4 shows the brake disc measurements and attenuation coefficient calculations. The calculations show

a difference in attenuation coefficient. The brake disc produced a lower coefficient compared with the steel block, which means the sound travelled more difficulty through the material; due to the value representing an inverse ratio between the number of decibels produced and the distance they have travelled. This is likely due to the difference in material properties, however the difference in thickness could also be a factor.

The brake disc also has a larger variation between the calculations, suggesting a greater difference in the microstructure compared to the rectangular block. This could be down to the component being worn down during use within certain areas, however this could be an unfair comparison as the background of the rectangular block is unknown.

5. Conclusion

Overall, an average attenuation coefficient of -0.102dB/mm has been calculated for the mild steel block. This value comes from five different measurement locations along the same side of the sample. For the brake disc the same method was used and an average attenuation coefficient of -0.471dB/mm was calculated. There are several reasons for the difference in values, such as different gains, thicknesses, materials, and material environments. The material for the brake disc was not specified however, it is likely to be cast iron. The density of cast iron is around 7300kg/m^3 whilst mild steel being around 7800kg/m^3 (The Engineering Toolbox, 2004). With a higher density it is expected to have a higher attenuation coefficient as fewer air gaps exist to reduce the propagation of the ultrasonic waves. Improvements in the investigation could include a higher number of measurement locations for both samples or testing samples of equal thicknesses.

Part 2: Through wall sizing accuracy analysis

1. Apparatus

- Ultrasonic Thickness Gauge

2. Introduction

Ultrasonic thickness gauging is a non-destructive analysis method to measure the thickness of components. It is mainly used where access to both sides of the material wall is not possible without cutting or drilling through the component. This allows for accurate measurements of a part which can then be reinstalled or assessed further for

information such as microstructure imperfections. This can be done for components that have been recently manufactured and used as a quality control. However, this process can also be used as a maintenance check on components that have already been assembled where dismantling them is not a viable option. Changes in thickness can indicate wear and stress that have been applied or defects that have occurred within the microstructure, hence the importance of conducting the testing and ensuring the results are accurate and reliable. Thickness gauging can also be used in defect determination which is the focus of this report.

In this report we will be assessing 210 defect measurements from 21 different defects done by 10 operators. The true size for each defect has been given alongside each of the operator's measurements. All the values are given to two decimal places and we will understand the accuracy of the operators using statistical analysis through Microsoft Excel. The data can be seen in Table 5.

Table 5: Defect Sizing Data

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

Linear regression is a key method used for each operator. A plot will be made of the true size versus the defect measurement taken by the operator, allowing visualisation of the difference in measurements. This creates a scatter plot where a linear trendline can be inserted. This will then allow for prediction of other defect sizes based on the trendline (IMB, n.d.). The linear plot also provides an R^2 value, where the closer to 1 indicates the overall accuracy of the measurements taken (Frost, 2018).

A normal distribution of the sizing errors will also be plotted where we can then understand how the variations in size change across the different defects and can then be compared to the different operators. The normal distribution will represent the proportion of defects within

a certain error range, for example, the percentage of defects within a 95% accuracy. This is created by calculating the average error and standard deviation across the range, then using the 'NORM.DIST' function in excel, a plot of given error values can be produced and compared. (Awati, 2022).

Ultrasonic imaging is a common use for defect analysis and is vital for quality checks on recently manufactured products. Additive manufactured products have a chance of forming these defects during the process due to the accuracy of laser sintering. A review taken place in 2020 investigated the use of ultrasonic on these components and found that there is sufficient potential for a detailed investigation. They suggest that phased array, laser ultrasonics and guided waves all show this potential. (Varvani-Farahani & Honarvar, 2020)

These techniques have also been used in monitoring water and sewage pipes where physical examination is not an option. Ultrasonic waves were used above 20kHz therefore significantly lower frequency than in this report; however they used bulk and guided waves to combat the lack of precision from the lower frequency.

They concluded that bulk wave sensors provided high sensitivity and mobile measurement, however there was a large cost from computational requirements. Ultrasonic phased array provided high sensitivity and fast detection speeds across a range of materials, however only within a short range. Finally, guided waves were accurate over long ranges, however, can only be used on high attenuation, non-metallic materials and the sensors must contact the pipes surface (Yu, Safari, Niu, Drinkwater, & Horoshenkov, 2021)

3. Measurements and Graphs

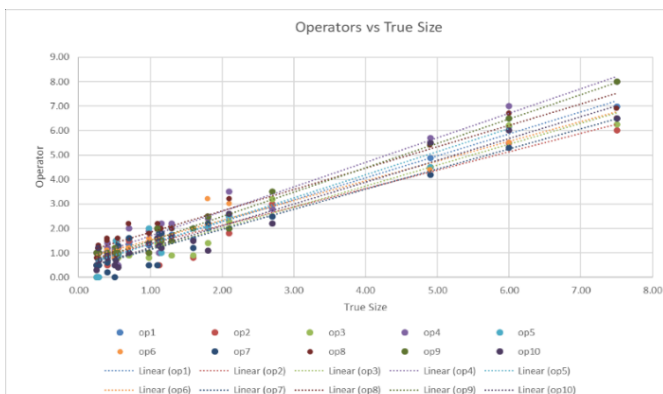


Figure 1: Operator vs True Size Trendlines

Figure 1 shows a plot of the defect true size versus the operators measured size for each of the twenty one defects recorded by the ten operators. The individual graphs can be found in Appendix 6.1

When looking at a graph like this it is important to note specific features to understand the data accurately. For example, with this graph it does not necessarily show the accuracy of one specific operator, however, it does provide a comparison between the operators. This then allows us to see which defects create the most error and therefore are most difficult to accurately measure which could be important for further investigation. The trendline allows for a visual representation of this along with the R^2 number.

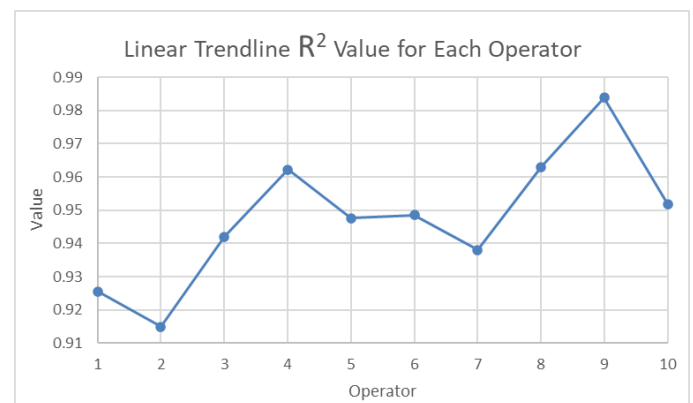


Figure 2: R^2 Value for Each Operator

Figure 2 shows the R^2 number for each of the operators, which has been calculated from the linear trendline where closer to 1, the more accurately the line fits the data. Comparing side by side again provides comparison of accuracy between each of the operators, however this does not necessarily suggest the accuracy of each individual measurement recorded.

A normal distribution can also be used to understand the variance and errors found for each operator. Calculating the difference between true and measured defect sizes gives the error of the operator, we can then calculate a mean and standard deviation of the errors using '=average()' and '=stdev()' function in excel respectively. Finally, we can then calculate the normal distribution using the '=NORM.DIST(x,mean,stdev,FALSE)' function. Once plotting the error versus norm.dist, a normal distribution graph for each of the operators can be produced.

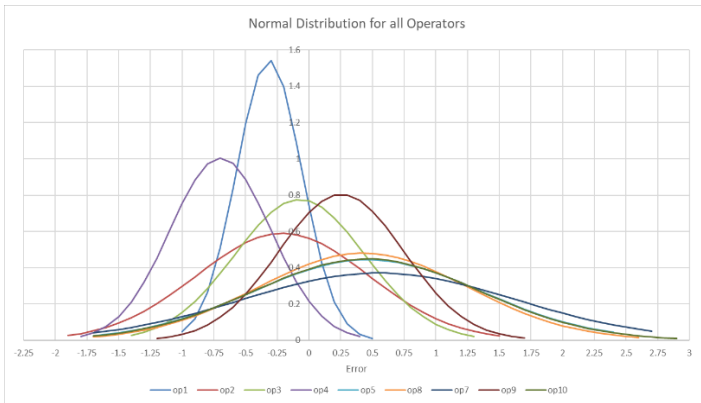


Figure 3: Normal Distribution for all Operators

When plotting the normal distribution, the error values for each of the operators can be extrapolated out to produce an accurate bell curve. This can be used to identify the accuracy of an operator and the variation in potential errors. This also indicates the error size which occurred the most, therefore quantifying which operators were most accurate. For each distribution, the minimum probability density was around 0.02 to prevent graphs of unnecessary size. Figure 3 shows each distribution overlaid into one graph where each of the individual graphs can be found in Appendix 6.2

4. Results and Discussion

Figure 1 shows the measured versus true size of each defect taken by every operator. This shows how the different operators vary for each of the defects. For example, on the right-hand side of the graph, operator 2 (red) measures a 7.5mm defect as 6mm, however operator 9 measures it as 8mm. Then in between these two points we can see the entire range for all the measurements where we can see operator 5 (light blue) came the closest at 7.05mm.

The plot also features a linear trendline for each of the operators, which represents how consistent an operator was. However, this also shows how the variation differs over all the defects. For example, defect E, the variation spread over 1.2mm, whereas by defect U, the variation is 2mm. Looking at this graph the operator with the highest overall accuracy can be found. This can be done by comparing all the measurements against the true size given and evaluating which trendline comes closest.

When plotting the true size of the defects an R^2 value of 0.9925 is calculated. As we know this is the true size of the defects and the values we are comparing to will be used as a base line. Figure 2 displays the R^2 value which has been

calculated for each of the operators, where we can see operator 9 came the closest with a value of 0.9839 and operator 2 performed the worst with a value of 0.9149.

However, the R^2 value does not determine the accuracy of the measurements taken compared to the true size, it only determines how well the trendline fits within the data. Since operator 9 produced the closest R^2 value, the trendline fits the data best without each measurement being the most accurate out of all the operators. This is the same case of operator 2.

Looking at the normal distribution graphs we can see the sizing defects as a function of their chance to occur (probability). The x-axis shows the error size and y-axis shows the probability of the error occurring. Figure 3 shows all the normal distributions for each operator laid over one another which allows for easy comparison between each operator. For an operator to appear most accurate the peak of the curve would need to be closest to 0 and have a limited range of errors.

For example, operator 1 shows a very high probability density of around 1.55 for a -0.3 sizing error, however the error range is between -1 and 0.5 which is small, suggesting consistent measurements whilst not the most accurate.

The most accurate operator would be operator 3, the peak of the curve is around -0.1, suggesting many of the errors would be within a -0.1 range. However, the range of the errors are between -1.4 and 1.3. Operator 9 appears accurate with a peak error around 0.25 and a range from -1.2 to 1.70, this also shows a slightly higher peak compared to operator 3 which suggests more of the results are within that 0.25 error.

Operators 4 and 7 are shown to be the least accurate. Looking at operator 4, this shows a tall error peak at -0.7, and a range between -1.75 and 0.35. Therefore, this operator produced consistently inaccurate results. Conversely, operator 7 shows one of the most varied set of results. This graph has a very low peak of around 0.6 for the error which suggests the results have little consistency in their accuracy. The range is also between -1.7 and 2.7, which is extremely large, therefore any results from this operator would be varied and inaccurate.

Another way to determine the accuracy of an operator based on their normal distribution would be to look at the 0 error intercept. This determines the likeliness of completely accurate measurements. Operator 3 intercepts this line at 0.7 (highest) and operator 4 intercepts this line at 0.2 (lowest), hence the evaluation of these operators to be the most and least accurate. Table 6 shows the y-intercept for each operator from the normal distributions, ranked highest to lowest.

Table 6: Y Intercept for Each operator

Operator	Y Intercept
3	0.768600293
1	0.735663644
9	0.70529048
2	0.562637671
8	0.420904687
10	0.393448172
5	0.389471138
6	0.331962419
7	0.325382459
4	0.21321833

5. Conclusions

Overall, using statistical analysis, an understanding of sizing measurement accuracy can be determined with the most accurate and least accurate operators being concluded. Looking at the linear regressions (figure 1), operator 9 appeared to be the most accurate with the closest R^2 value to the true defect size graph, therefore producing the most consistent results. Operator 2 was then found to perform the worst with the smallest R^2 value.

Comparing these results to the normal distributions (figure 3), operator 9 was found to be one of the most accurate, with the peak around 0.25 suggesting many of the measurements will be within a 0.25 error. Operator 2 then had a very large range of probable errors. Looking at the operators and both the statistical analysis methods, it justifies the conclusions that operator 3 or operator 9 are the most accurate, however when looking for the least accurate operator, linear regression suggests operator 2, whilst the normal distribution suggests operator 4 or 7. This shows there are some discrepancies within these methods, potentially down to the data only being to two decimal places and suggesting further investigation would be required. With the measurements being taken to two decimal places, this could create inaccuracies. Using angled reflection could also provide a more detailed image and therefore a more accurate sizing measurement.

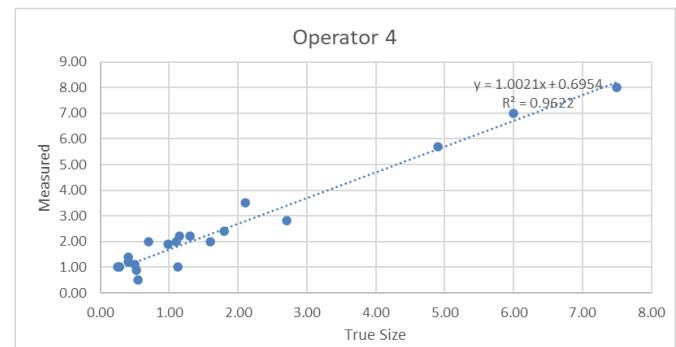
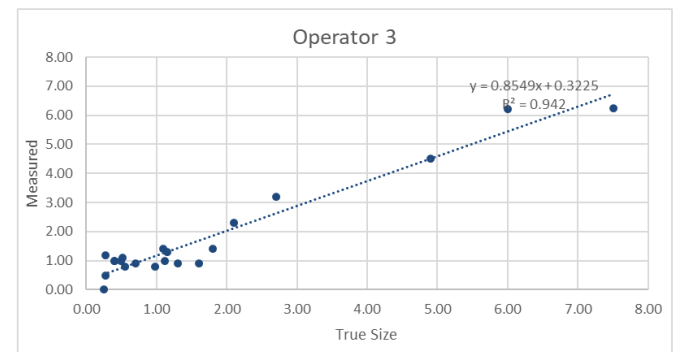
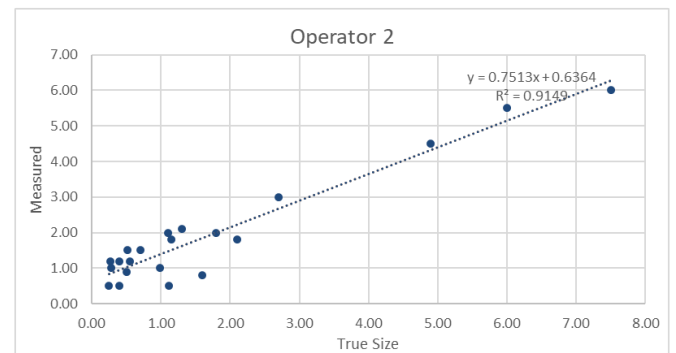
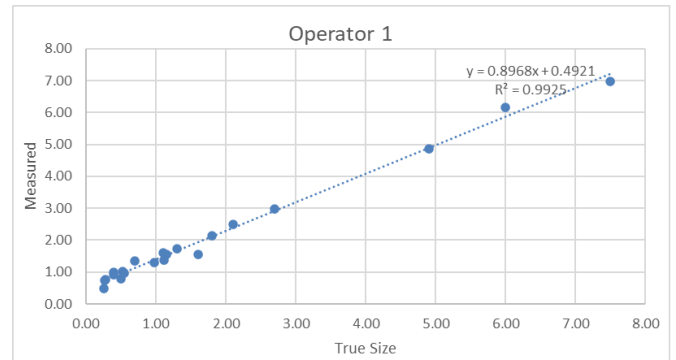
6. References

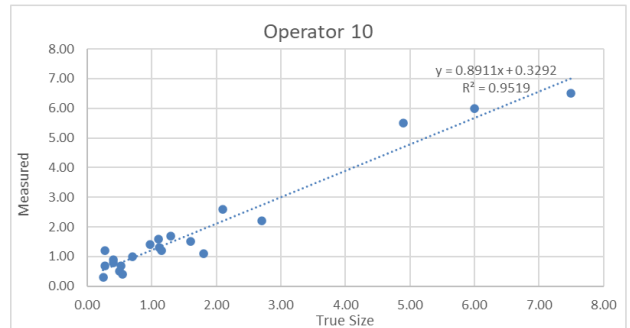
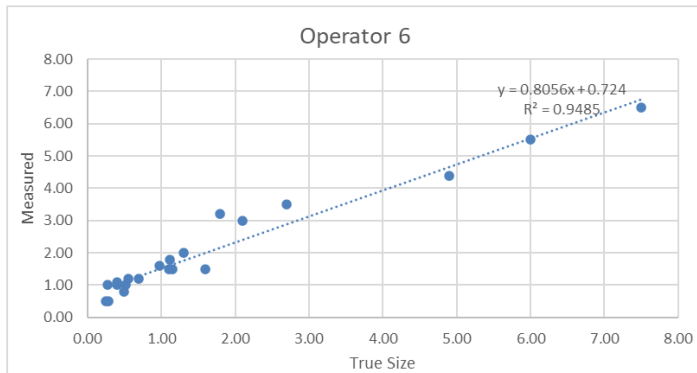
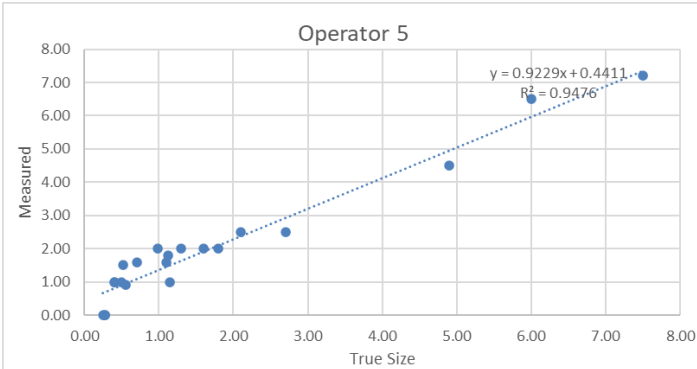
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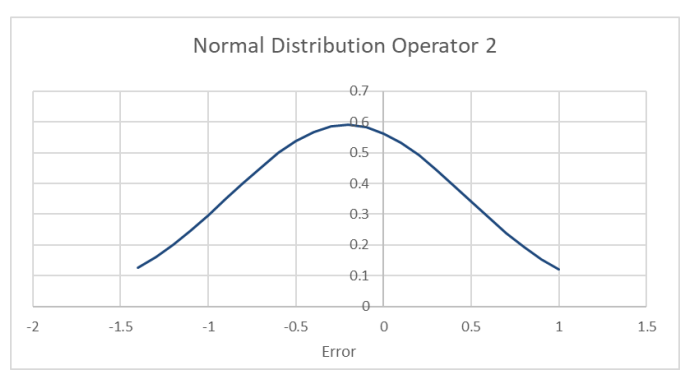
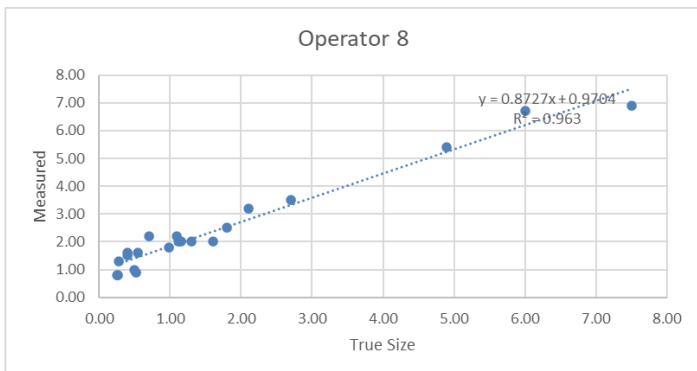
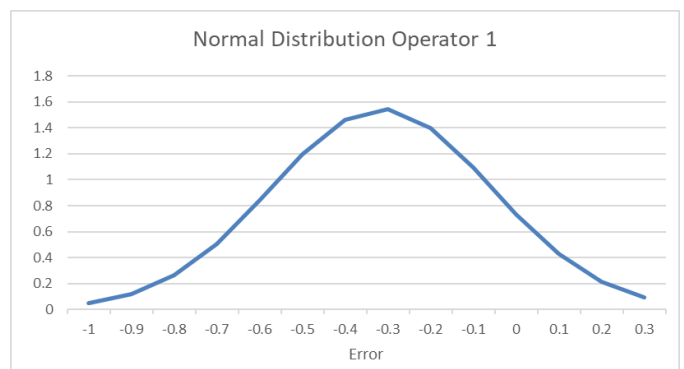
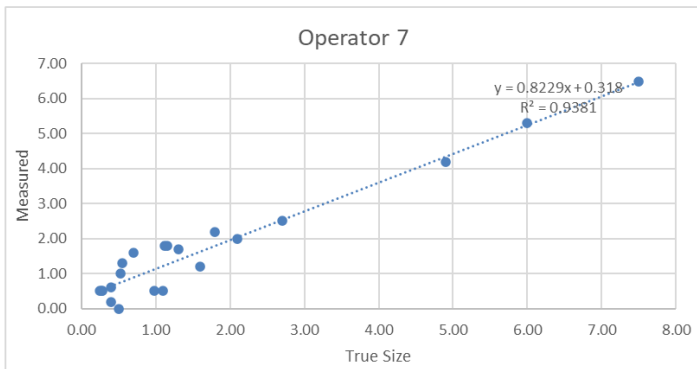
6. APPENDIX

6.1 Operator vs True Size Graphs

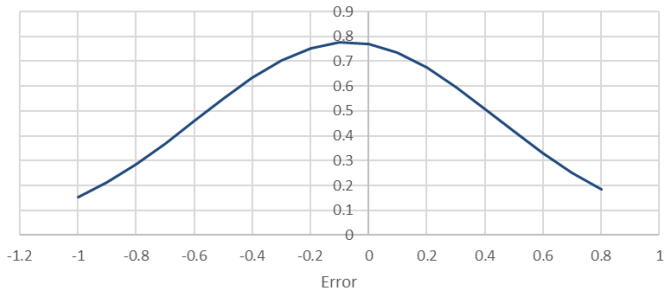




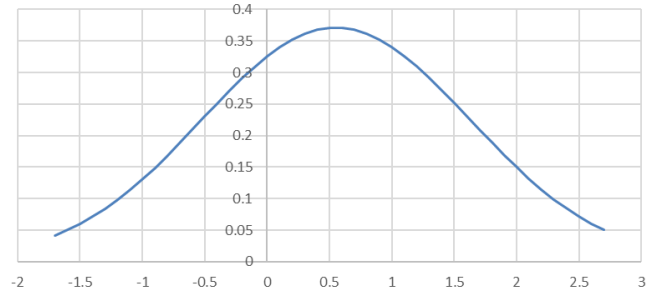
6.2 Normal Distributions for Each Operator



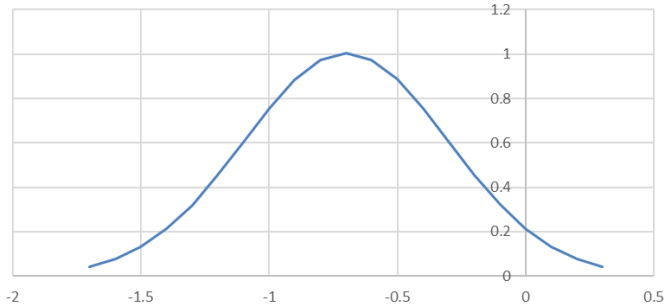
Normal Distribution Operator 3



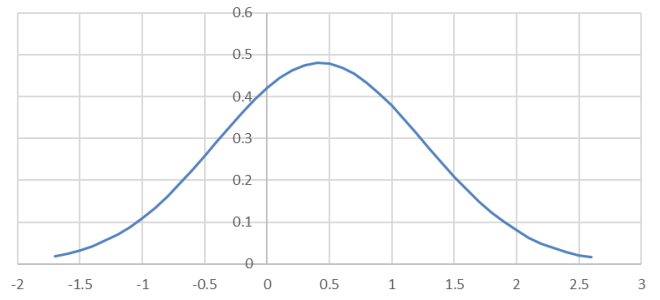
Normal Distribution Operator 7



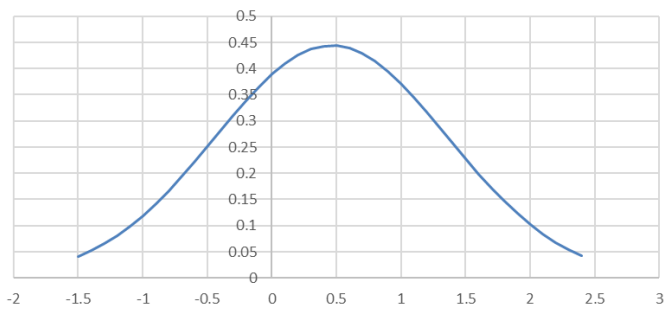
Normal Distribution Operator 4



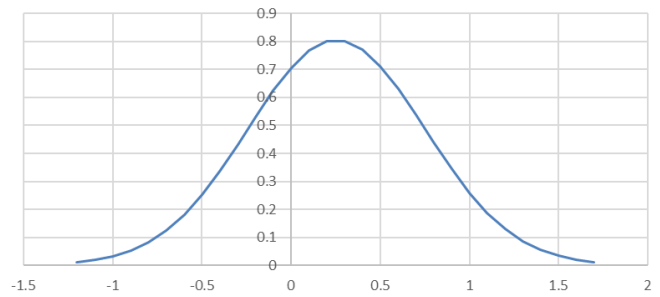
Normal Distribution Operator 8



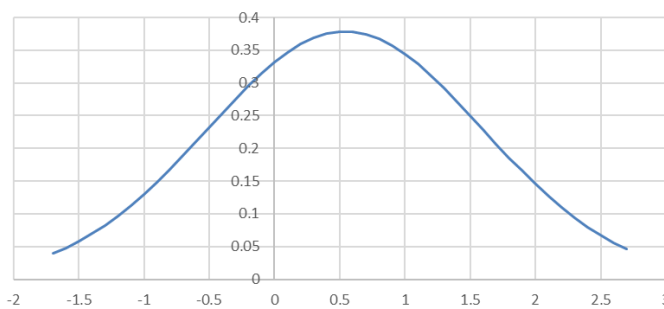
Normal Distribution Operator 5



Normal Distribution Operator 9



Normal Distribution Operator 6



Normal Distribution Operator 10

