

Ultrasonic Attenuation Coefficient Determination and Probability of Sizing Analysis

Nathan Watson

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Abstract

This report covers Ultrasonic wave attenuation coefficient determination as well as through wall sizing statistical analysis. Results were taken from an A-scan of multiple locations over two components. The amplitude of the waves of these scans were then used to determine the attenuation coefficient of each material. The through wall sizing procedure was analysed by determining accuracy of measurements of each defect presented as well as all measurements by each operator against true size. This accuracy was compared using normal distribution and the procedure was criticised. In this sample, the probability of detection is low at defects <0.5mm. Accuracy is also low and increased with defect size. The effect of different operators is also clear, as consistency in accurate measurements fluctuates.

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1 Ultrasonic Attenuation Coefficient Determination

1.1 Apparatus

For this work an Silverwing D-SCAN ultrasonic flaw detector [1] has been used alongside a 5MHz zero-angle probe. A Propylene Glycol-based hair gel product was used in place of a dedicated ultrasound gel. This equipment is commonly used for NDT and in this case was used to analyse structural flaws in two components: a section of steel bar and an automotive brake disc.

1.2 Introduction/ Method/ Procedure

Non destructive testing (NDT) refers to a range of methods of evaluating materials and components without damaging the test subject. NDT is used in many industries and is critical in engineering due to the consequences of failure[2]. Ultrasonic flaw detection is an NDT method which allows for testing of internal defects. Phased array ultrasonic testing (PAUT) allows for signals to be generated at different distances and angles to analyse defects in materials with structures/other defects which affect the quality of results. It can detect defects less than 1mm with good accuracy[3]. These signals are created by a transducer, in this case a 5MHz piezoelectric crystal which resonates due to an applied electrical pulse. The images produced by this method of testing are categorised by letter, A, B, C, D-Scan for example. This refers to the direction of the view into the material. An A-Scan was used in this experiment which provides a 2d image of echo amplitude against time.

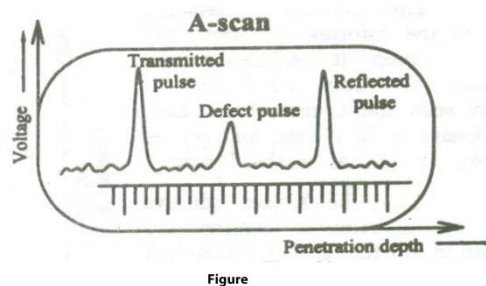


Figure 1 A-Scan diagram[4]

The frequency of the waves passing through the material diminish with distance due to scattering and absorption. This results in the amplitude of each back wall reflection decreasing and is what is known as attenuation. ToF methods allow for the attenuation to be calculated by comparing the difference in dB between reflections and dividing by the time between them.

1.3 Measurements and graphs of raw data

The components tested were a rectangular mild steel bar and an automotive steel brake disc, with two faces of each analysed. The steel bar measured ~80mm in length and ~19mm in thickness. 5 locations, roughly equally spaced along two non-opposite faces were used for the bar, resulting in 10 measurements. 5 locations on the mounting section and 5 locations on the friction area were used on the brake disc, resulting in 10 measurements.

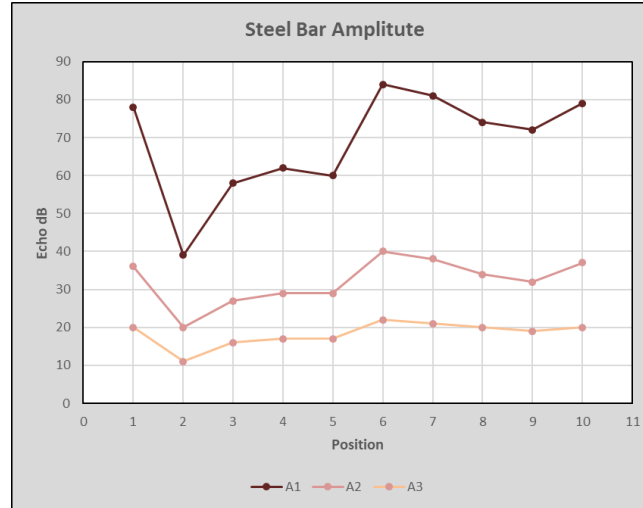


Figure 2 Steel bar echo amplitude

Figure 2 shows the amplitude of the first three reflections at each position on the steel bar. Positions 1-5 represent one face and 6-10 represent the other. This is consistent for the rest of the data. A gain of 36dB was maintained for all points. It is important to note that the depth of material may fluctuate within 0.2mm at any point, this is due to the low quality measurement device used to gauge the thickness being unable to provide consistent results, therefore a close constant of 19mm was assumed throughout.

1.4 Calculations and error estimation

As stated above, the attenuation coefficient (a) can be calculated using ToF. This represents the rate of decay of the ultrasonic wave.

$$a = -\left(\frac{20}{d \cdot 4}\right) \cdot \text{Log}\left(\frac{A_3}{A_1}\right) \quad \text{Equation 1 Attenuation Coefficient}$$

Where: d = distance of travel

This formula results the attenuation coefficient between the first and final reflection, in this case a small sample of only 3 points. Each reflection travels twice the distance of the thickness of material, therefore when measuring over two reflections, the distance must be multiplied by 4.

1.5 Results and Discussion

Using the formula above the attenuation coefficients can be calculated and the normal distribution at each point plotted. This data is partially incomplete due to the measurements of the brake disc friction area being poor, this reduced the sample size by half and is therefore not as accurate.

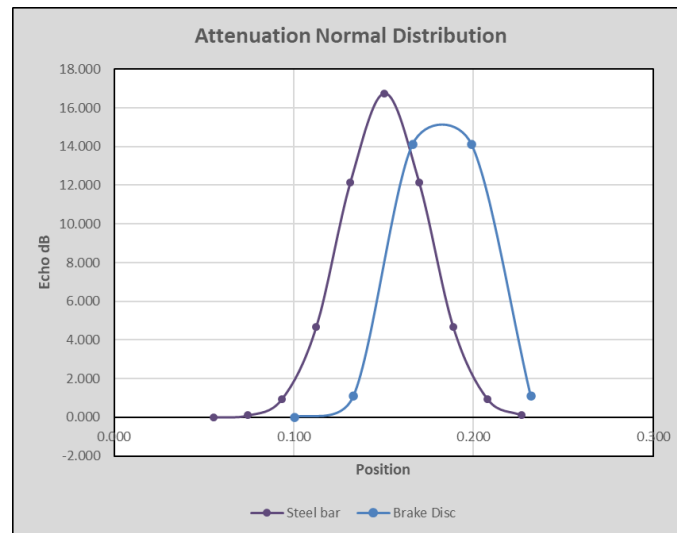


Figure 3 Normal Distribution of Attenuation

Figure 3 shows the normal distribution of the amplitudes at each point. The attenuation coefficient is the centre point of the bell curves being 0.151 for the bar and 0.183 for the brake disc.

2 Through Wall Sizing Accuracy Analysis

2.1 Introduction/ Method/ Procedure

Probability of detection (PoD) is a method used in NDT to determine the likelihood of a defect being found. It is commonly used to analyse the effectiveness of different NDT methods and techniques. Results from a PoD analysis are often displayed with a curve ranging from 0 – 1, with higher values representing higher probability. Certainty of result is often displayed with confidence bands where a narrow band represents high probability. Larger sample sizes usually have narrower confidence bands, this can be useful in determining minimum sample sizes for a given certainty[5].

Using a sample of 21 defects measured by 10 operators, statistical analysis is undertaken to determine the accuracy of the sizing. It is important to consider that error may be present due to the equipment, the procedure, and the operator of the experiment. This provides multiple approaches to analysis, grouping each operator's data set as well as each defects data set.

2.2 Measurements and graphs of raw data

The sample of data shows 21 defects labelled A-U accompanied by the true size. A set of 10 measurements by a group of operators are provided also.

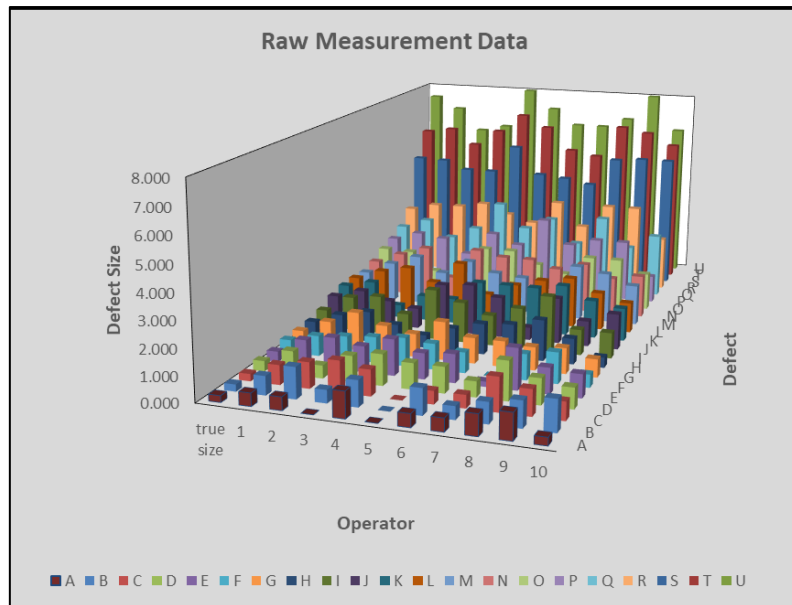


Figure 4 Raw sizing accuracy data

Figure 4 represents the measurements of each defect by each operator in comparison to the true size. True size is displayed in the leftmost row. Already it is easy to see that there is variation in results, as well as multiple defects not detected. The defects which were not detected as well as the operators who missed them are shown in the figures below.

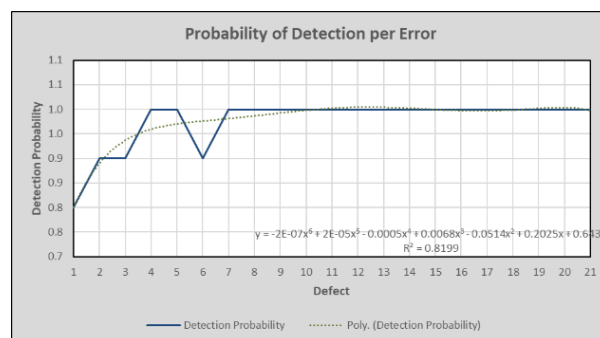


Figure 5 PoD per defect

Figure 5 shows the detection rate of each defect as labelled and shows a lower probability of detecting the first defects. In this sample these are defects up to around 0.5mm.

The mean measurement of each defect is shown in figure 7 against the true size. This gives a good representation of the range of measurements within the sample.

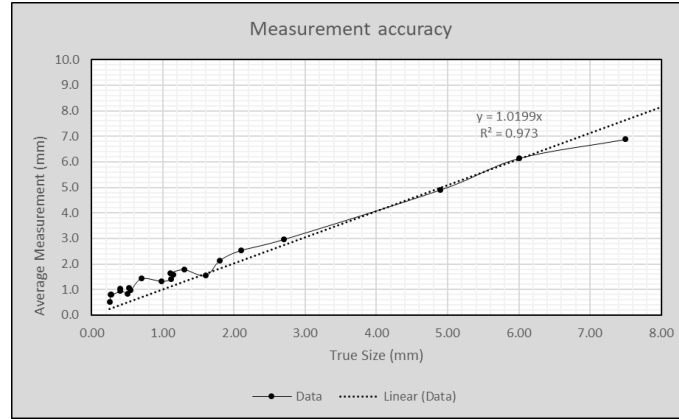


Figure 6 Defect True size against mean

2.3 Calculations and error estimation

2.3.1 Mean and Confidence Intervals

Multiple approaches to analysing the data were undertaken. The first step was to consider only the error of measurement in each case, equal to the absolute value of the true size minus the measured size. The absolute value is used to ensure accuracy as large errors in opposite directions may work to cancel each other out and therefore provide a false result close to that of the target.

A mean error is then calculated for each defect and each operator. Interestingly the mean average is equal for the defects and operator errors, however this seems to be a coincidence. To plot a credible dataset, confidence intervals are calculated for 95% accuracy, shown below.

Equation 2 95% Confidence Interval

$$x \pm Z \cdot \frac{s}{\sqrt{n}}$$

Where: x = mean

Z = Z value for given confidence, (1.96 for 95%)

s = standard deviation

n = sample count

As this is a sample of data the appropriate standard deviation equation must be used, in this case:

$$s = \sqrt{\frac{\sum(x - \bar{x})^2}{n-1}} \quad \text{Equation 3 sample standard deviation}$$

Normal distribution is a good way to display multiple data points in relation to the mean. Calculating this allows visualisation of a bell curve. In equation 4 μ represents the mean and σ represents standard deviation.

$$f(x) = \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{1}{2}\left(\frac{x-\mu}{\sigma}\right)^2}$$

Equation 4 Normal Distribution

2.3.2 Visualised Data

A plot of the mean absolute error per defect is shown below.

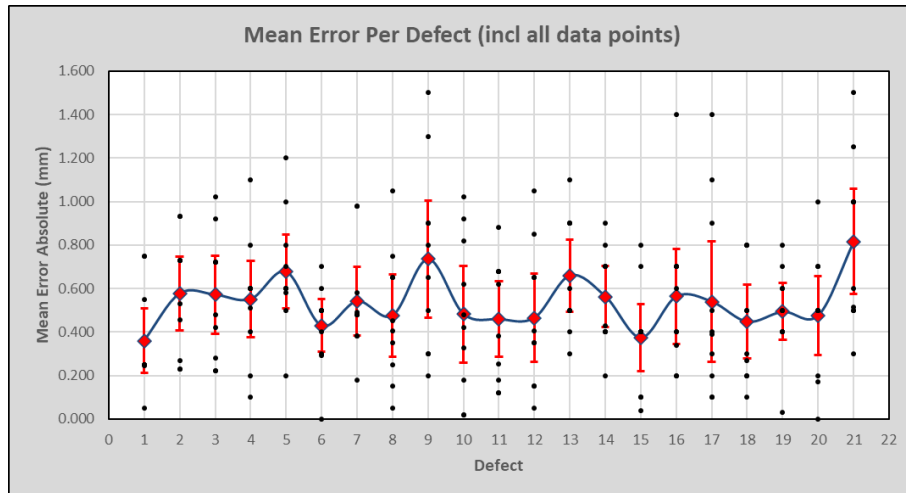


Figure 7 95% Mean Error per Defect

Figure 8 highlights every measurement error for each defect in relation to the error mean. The error bars trend to increase as the defect size increases. Figure 9 shows the same data but per operator.

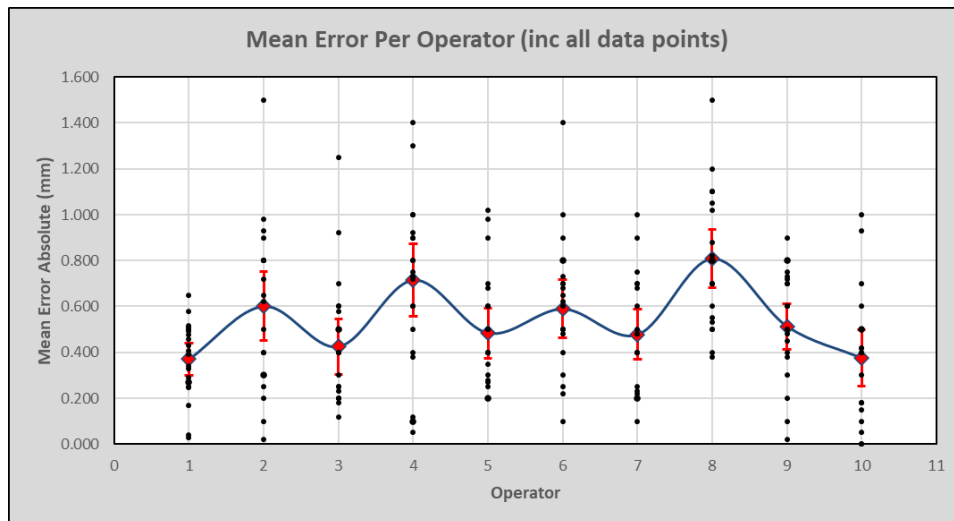


Figure 8 95% Mean Error per Operator

The operator error data shows all the measurements made by each operator in relation their average. In this case there is no trend, however each operator has a different level of consistency.

Percentage error can be found by dividing the measured defect by its true size. Figure 10 displays measurements as a total percentage of the true size. Red values highlight an error of sizing error of 50+%, orange represents 10-50%, and green represents errors up to 10%.

		Operator											
Defect		1	2	3	4	5	6	7	8	9	10		
	A	198	200	0	400	0	200	200	320	400	120	255	204
	B	269	444	185	370	0	370	185	296	370	444	326	294
	C	271	357	429	357	0	179	179	464	357	250	316	284
	D	228	125	250	300	250	250	150	375	250	200	238	238
	E	245	300	250	350	250	275	50	400	250	225	260	260
	F	158	180	200	220	200	160	0	200	240	100	184	166
	G	195	288	212	173	288	192	192	173	192	135	204	204
	H	174	218	145	91	164	218	236	291	182	73	179	179
	I	193	214	129	286	229	171	229	314	143	143	205	205
	J	133	102	82	194	204	163	51	184	102	143	136	136
	K	123	45	89	89	161	161	161	179	134	116	126	126
	L	135	157	113	191	87	130	157	174	130	104	138	138
	M	145	182	127	182	145	136	45	200	182	145	149	149
	N	133	162	69	169	154	154	131	154	115	131	137	137
	O	98	50	56	125	125	94	75	125	125	94	97	97
	P	119	111	78	133	111	178	122	139	139	61	119	119
	Q	119	86	110	167	119	143	95	152	95	124	121	121
	R	110	111	119	104	93	130	93	130	130	81	110	110
	S	99	92	92	116	92	90	86	110	112	112	100	100
	T	103	92	103	117	108	92	88	112	108	100	102	102
	U	93	80	83	107	96	87	87	92	107	87	92	92
		159	171	146	202	160	170	131	218	184	142		
		159	171	139	202	137	170	124	218	184	142		

Figure 9 Percentage Defect

This chart can be referred to when analysing the bell curves to give a greater understanding of where the errors come from. It also shows clearly defects that went undetected. The outer columns represent mean percentage error, with the first dataset omitting undetected defects.

2.4 Results and Discussion

The normal distribution of the defects show that the measurement of small defects resulted in smaller errors.

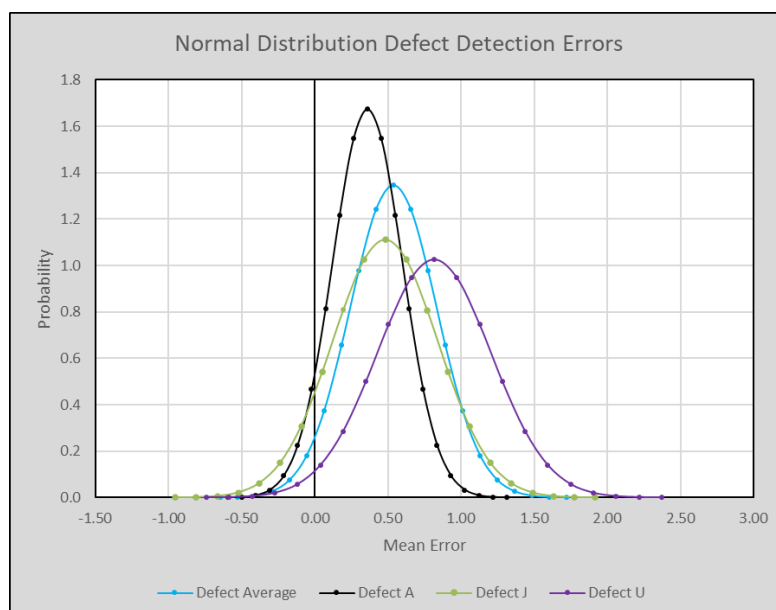


Figure 10 Defect normal distribution

Figure 11 shows that the smallest defect not only had smaller measurement errors in size, but also had tighter grouping. However, when the mean error is displayed with the percentage error, it is clear to see that the accuracy of measurement increases with the defect size, shown in figure 12.

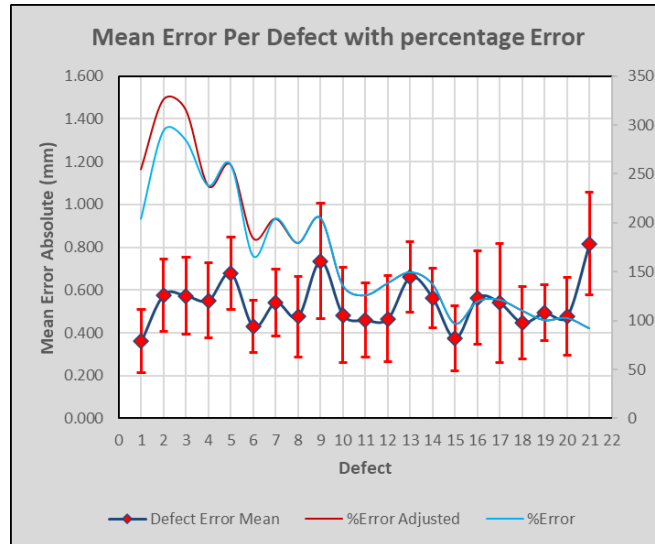


Figure 11 Mean absolute Error with percentage error

The normal distribution of the operators shows that each operator has a larger spread in accuracy than each defect, shown by a shallower average curve.

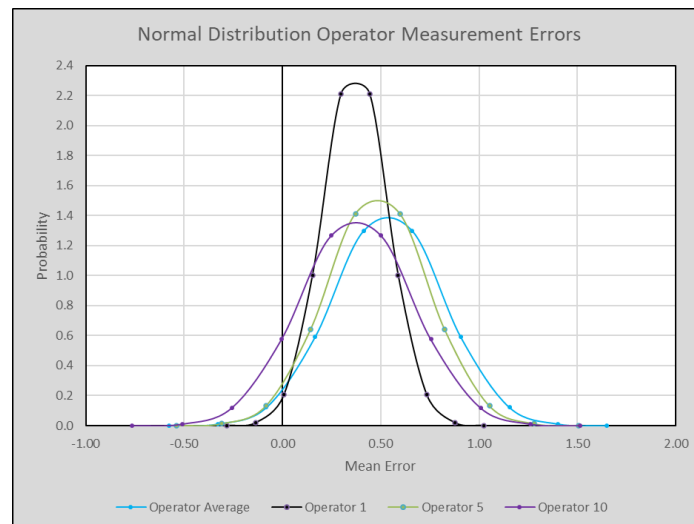


Figure 12 Operator Error Normal Distribution

Figure 13 also shows how one operator can produce more consistency when measuring defects, as shown by operator 1 having a steep curve, with a higher chance of measurement being close to the mean.

In figure 14 the percentage errors for operators track with the absolute error. This could be useful to review when optimising the procedure to use the more accurate operators only.

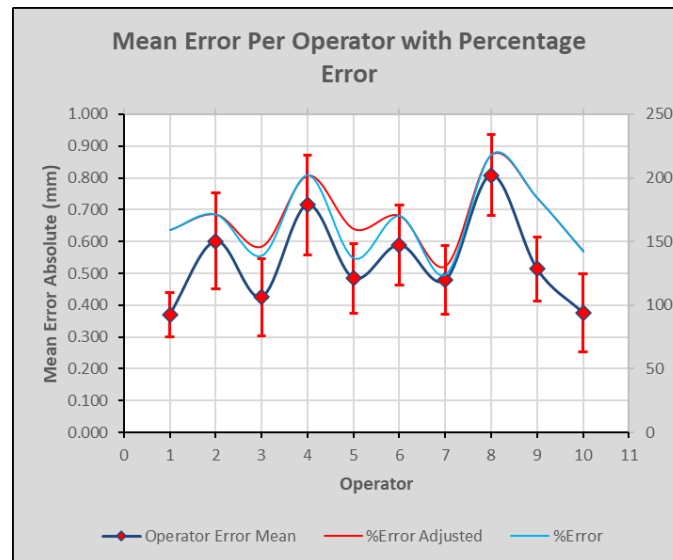


Figure 13 Operator normal distribution with percentage error

2.5 Conclusion

2.5.1 Attenuation

The attenuation coefficient determination can be performed easily with the method described. The difference in attenuation coefficients arise from the different materials of components, unsurprisingly the steel block which has a consistent surface finish provided results with a higher accuracy. The brake disc data was recorded poorly and had half the sample size, as such it is as expected that the results are less accurate.

2.5.2 Through wall sizing

The analysis of the through wall sizing shows that accuracy of measurement increases with defect size. Defects up to 0.5mm have a large percentage error and an increased chance of not being detected. Although larger defect sizing is more accurate, the absolute error does increase with defect size. The data also shows that some operators are more accurate than others, meaning that the procedure could be more done better by using higher skilled operators.

3 References

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- [2] M. Gupta, M. A. Khan, R. Butola, and R. M. Singari, "Advances in applications of Non-Destructive Testing (NDT): A review," *Advances in Materials and Processing Technologies*, vol. 8, no. 2, pp. 2286-2307, 2022, doi: 10.1080/2374068x.2021.1909332.

- [3] H. Taheri and A. A. Hassen, "Nondestructive Ultrasonic Inspection of Composite Materials: A Comparative Advantage of Phased Array Ultrasonic," *Applied Sciences*, vol. 9, no. 8, p. 1628, 2019, doi: 10.3390/app9081628.
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