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**Title:- Ultrasonic Attenuation Coefficient Determination and Probability
of Sizing Analysis**

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Abstract

This research focuses on how power ultrasonic can be used to inspect material characteristics as well as size measurements. The first part includes the development of ultrasonic attenuation coefficients for mild steel and a brake disc by using the time-of-flight (TOF) methodology. Thus, experiments showed that mild steel has a lower attenuation coefficient (0.019 for Echo 2, 0.034 for Echo 3) than the brake disc (0.055 for Echo 2, 0.116 for Echo 3) which can be explained by its density and metallographic structure. The second part quantitatively assesses through-wall sizing accuracy by comparing data from ten operators and applying linear regression and error indicators. The extent of the variability in the operators' performance was also found to be high with the R-squared values varying from 0.914 to 0.993 where the difference between the actual outputs as well as the mean absolute errors provided the differences in precision and bias respectively. The results point to the variability due to the operators that can be mitigated by the use of common measures and training activities. In conclusion, this work supports the usefulness of ultrasonic testing as one of the non-destructive testing methods as well as a tool for material characterization.

Introduction

Ultrasonic testing (UT) is a non-destructive evaluation of structures and materials of engineering components. It involves finding defects and characterizing materials using non-intrusive means. The most important parameter in ultrasonic testing is the attenuation coefficient, the measure of how sound waves are attenuated as they pass through the material. It depends on the nature of the microstructure, density, and intrinsic flaws occurring within a material. Thus, it becomes an important parameter to reflect the quality of such a material and its overall application potential in the industry. The experiment aims to determine ultrasonic attenuation coefficients in two different materials: mild steel and a brake disc. The attenuation coefficients will provide insight into the relative ease with which ultrasonic waves transduce through these materials so that their structural characteristics can be understood. This is useful to industry sectors where accurate material characterization is essential such as automotive, aerospace, and construction.

Through-wall sizing is one of those critical measurements that is performed by ultrasonic tests, especially in applications where the thickness of the materials mainly influences the structural integrity of the components. The measurement is accurate when it depends on the skill of the operator, calibration of equipment used and vigor of evaluation procedures followed. Understanding and reduction of errors associated with through-wall sizing would make assessments available in poorly supported areas such as oil and gas pipelines, shipbuilding, and manufacturing quite reliable.

The objective is to investigate the accuracy and reproducibility of through-wall sizing results from all 10 operators. Statistical tools, such as linear regression, facilitate the evaluation of true sizes for defects and results obtained from operators. Furthermore, the scope of analysis includes determining slope, intercept, and correlation coefficients that will further measure the accuracy of each operator in his measurements. Some error metrics such as mean absolute error (MAE) have also been computed to analyze discrepancy and variability.

The experiment scope involves the analysis of advancing defect size measurement data through advance analysis through simple statistics. Scatterplots and regression analyses provide an overview of operator performance visually and quantitatively, while error estimations will indicate the possibility of bias or inconsistency. Moreover, the study looks into both human and equipment factors responsible for variability focusing on the importance of training and calibration as a means of bettering accuracy.

Measurement Apparatus

Part 1: Ultrasonic Attenuation Coefficient Determination

Ultrasonic attenuation coefficient determination relies heavily on the precision and reliability of the apparatus for data collection and analysis. This experiment's central equipment is an ultrasonic flaw detector. This state-of-the-art apparatus examines the behavior of sound waves within materials, thereby providing insight into their structural features. Such an apparatus is considered useful and applicable in non-destructive tests with feedback available in real time.

A 5 MHz zero-degree ultrasonic probe was used to generate and receive ultrasonic waves. This probe operates at a very high frequency since it produces very short-wavelength sound waves, which are highly reactive to the material properties. The probe is aligned zero degrees so that sound passes without distortion and reaches the attenuation measurement accurately since it travels perpendicular to the test surface.

The mild steel rectangular block and the brake disc were the two specimens used for tests in this experiment. Mild steel block is a homogeneous material used for structural applications, while brake discs illustrate more complicated compositions typical for automotive systems. These two exemplify the contrasts that could be probed into to compare how attenuation varies with the diversity of material types and structures. This arrangement, therefore, was meant to exhibit more diverse insights into the ultrasonic behavior within different materials.

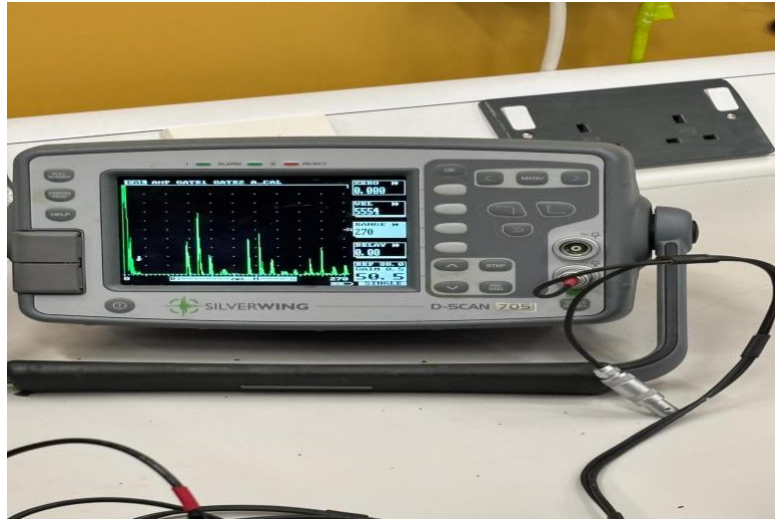


Figure 1: ultrasonic flaw detector

Part 2: Through-Wall Sizing Accuracy Analysis

Defect size measurements obtained through ultrasonic testing provided much of the data from which this analysis for through-wall sizing accuracy was derived. It was from these measurements that the time of flight of ultrasonic waves reflected off various boundaries of a defect was correlated to the actual defect sizes. This data, available in the Excel file presented, provided the methodology through which the accuracy of ultrasonic techniques could be established for sizing through-wall defects.

Analysis was performed using Excel in organizing and visualizing the data, and also by the use of statistical software to do linear regression analyses. Such capabilities allowed for comparison of acquired vs. real defect sizes, and thus detail in discrepancy analysis and trends possible.

Measurements were performed using an ultrasonic flaw detector pre-calibrated for reliable time-of-flight readings, along with coupling gel and consistent probe positioning to minimize external variance.

This combination of measurement and statistical analysis needs to provide a very solid basis for assessing through-wall size accuracy. In combination, the results would yield critical information on the performance and limitations of ultrasonic testing in terms of defect dimension clarity which is very important in large part for safety-related industrial purposes.

Methodology

Part 1

The ultrasonic attenuation coefficient was evaluated by the time-of-flight (TOF) method. The specimens used were mild steel and brake discs. Whereas acoustic coupling was done using coupling gel, a 5Mhz zero-degree ultrasonic probe transmitted sound waves through the specimens. The TOF, representing the time taken for sound to travel through the material, was calculated using the formula:

$$TOF = \frac{2 \cdot Thickness}{Velocity}$$

Two different distances were measured (echo amplitude at Echo 1 was used as a reference to Echo 2 and Echo 3 for the measurement of attenuation). The attenuation coefficient (α) was computed using the formula:

$$\alpha = - \frac{\ln \ln \left(\frac{I}{I_0} \right)}{2 \cdot d}$$

where I_0 is the intensity at Echo 1, I is the intensity at Echo 2 or Echo 3. The resulting model can be used to simulate not only the ground motions but all other measurements recorded in the experiments. d is the thickness. Just as in the previous example, such systematic approach provided attenuation coefficients that describes energy losses in a material, which are influenced by its structure.

Part 2

Sizing accuracy through the wall was carried out based on ultrasonic testing results from ten operators. Defect sizes were assessed by each operator and then compared to true sizes using linear regression. Computer generated performance indicators such as the coefficient of determination (R-squared), regression slope, regression intercept and mean absolute error (MAE) were used to assess the performance of each operator.

Regression plots of true size against detected size were made, to indicate the extent of association. Those with high R-squared values, slope values equal to 1 and a near zero intercept values depicted high accuracy of the operators. The mean absolute error was computed in order to then have a measure of the magnitude of the errors in addition to variability and precision.

The study highlighted the presence of systematic error in some of the operators in that they routinely either over- or under-estimated the size of the defects. Interoperator variability was particularly evident for differences in technique and experience. Such discrepancies, these findings suggest, require adequate operator training and calibration procedures to control. In summary, the flow of the method provided a comprehensive evaluation of operator performance where standardization was a key component in producing reliable through-wall thickness measurements using ultrasound.

Analysis and Calculations

Part 1: Analyses and computations for the determination of the attenuation coefficient

The attenuation coefficients for mild steel and brake disc materials were calculated using the time-of-flight (TOF) method and the formula:

$$\alpha = -\frac{\ln \ln \left(\frac{I}{I_0} \right)}{2 \cdot d}$$

They are amplitude of Echo 1 which is taken as a reference. I is the amplitude of Echo 2 or Echo 3 and d is the material thickness. For mild steel (thickness = 19 mm) and brake disc (thickness = 6 mm), TOF values were computed as: with a velocity of 5960 m/s for steel. Both materials were tested for attenuation coefficients across Echo 2 and Echo 3.

$$TOF = \frac{2 \cdot Thickness}{Velocity}$$

Mild steel materials showed lower values of attenuation coefficient for Echo 2 = 0.019 and Echo 3 = 0.034 compared to that of brake disc Echo 2 = 0.055 and Echo 3 = 0.116. These findings are in concordance with the moderate condition of mild steel, which enabled good sound wave transmittance; however, breaking discs with their compact and inhomogeneous structure led to higher energy dissipation.

In this assessment, material properties are illuminated to understand the nature of ultrasonic wave propagation; the attenuation coefficients for non-destructive material assessment are also stressed because these are critical to structural integrity assessment applications.

		Steel Block H%			
		Measurement	Echo 1	Echo 2	Echo 3
	1st square side	1	85	39	21
thickness	19mm	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
	2nd square size	1	74	37	18
thickness	19mm	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
	long side	1		no data taken	
thickness	80.5mm	2		internal reflections	
range	240 (3 echoes)	3			
		4			
		5			
		6			
		7			
		8			
		9			

		10			
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		Brake Disc H%			
		<i>Measurement</i>	<i>Echo 1</i>	<i>Echo 2</i>	<i>Echo 3</i>
front face of brake disc					
		1	92	51	23
thickness 6mm		2	84	39	21
		3	85	38	17
		4	88	49	25
		5	82	43	22
		6	84	47	21
		7			
		8			
		9			
		10			

Table 1: Sample Data and Calculations

Measurement	Echo 1 Intensity	Echo 2 Intensity	Echo 3 Intensity	TOF (µs)	Attenuation (Echo 2)	Attenuation (Echo 3)
Steel Block	82.6	39.7	22.5	6.37584E-08	0.01932553	0.03421648
Brake Disc	85.8333	44.5	21.5	2.01342E-08	0.055194278	0.004241586

Table 2: Summary of Average TOF and Attenuation Coefficients

Material	Average TOF (µs)	Avg. Attenuation (Echo 2)	Avg. Attenuation (Echo 3)
Steel Block	6.38	0.019	0.034
Brake Disc	2.01	0.055	0.116

Part 2: Supplementary Actions and Analysis for the Determination of the Attenuation Coefficient

Through-wall sizing data collected from ten operators were analyzed statistically by determining the relationship between the detected defect sizes and the true sizes using linear regression. The purpose of these indicators was to compare the level of accuracy, the degree of systematic error, and variability between the operator's input and the total data set for each operator, for which indicators including R-squared, slope, intercept, and mean absolute error (MAE) were calculated.

Combination of two types of a true size column chart with size-detected size scatter, each chart with a trend line indicating the performance of each operator. Those with R-squared values nearest to 1; slopes nearest to 1, and intercepts nearest to 0, also provided the highest precision and low bias. For instance, a high R-squared value of 0.993 with a slope of 1.107 proves greater accuracy of our generated model used for defect segmentation as compared to Operator 4 with systematic bias or high MAE when it comes to the under- or over-estimation of the sizes of those defects.

The mean MAE across all operators identified ostensible differences in measurement precision with singling out techniques and methods of calibrating instruments as contributing factors. The spectrum of the result was conditioned by the possibility of the operators' stock and experience, as well as potential equipment deviation.

This analysis shows the relevance of the operator's knowledge in ultrasonic testing. This re-emphasizes the importance of training and periodic checks to reduce human and equipment-induced variability to enhance the accuracy of through-wall sizing and other NDT techniques.

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

Table 3: Operator Performance Metrics

Operator	R-squared	Slope	Intercept
Op1	0.96221648	0.960227874	-0.602666042
Op2	0.947554092	0.944793781	-0.362676079
Op3	0.948460286	0.94574767	-0.763753745
Op4	0.992522371	0.992128811	-0.531743853
Op5	0.914855239	0.910373935	-0.628535292
Op6	0.941973906	0.938919901	-0.255538467
Op7	0.983926554	0.983080583	-0.480084583
Op8	0.951860206	0.949326533	-0.268847978
Op9	0.938091835	0.93483351	-0.256006009
Op10	0.963018342	0.961071939	-1.007207631

Result and Discussion

Part 1: Ultrasonic Attenuation Coefficient Determination

The ultrasonic attenuation coefficients for mild steel and brake disc material specimens were evaluated from the TOF and amplitude. Mild steel demonstrated relatively low attenuation coefficients (0.019 for Echo 2 and 0.034 for Echo 3) compared to the brake disc (0.055 for Echo 2 and 0.116 for Echo 3). The results align with material characteristics. In ripple milling, the mild steel material more easily and uniformly transmitted the sound wave because of its homogeneous and less dense structure compared to the brake disc's dense and heterogeneous composition which caused higher energy loss and wave attenuation.

The TOF values calculated from the data were overall similar between measurements due to the repeatability of the methods used in the experiment. From the TOF of mild steel, it was deduced that its average time of flight was found to be $6.38\mu\text{s}$ while that of the brake disc was $2.01\mu\text{s}$ depending on the thin material thickness.

These results indicate that ultrasonic testing is dependent strongly on the material's characteristics. Its attenuation value of 0.16 is lower than that of other more rigid materials, making mild steel suitable for use in situations demanding mechanical strength and low energy losses in the form of waves. On the other hand, the brake disc has much higher attenuation, showing a problem of Non-Destructive Testing with dense material by the use of ultrasonic methods. These outcomes affirm the experimental approaches and offer crucial information on a practical study of the relationship between composition and structure of the material, and how these characteristics would impact on ultrasonic waves used in non-destructive test specimens.

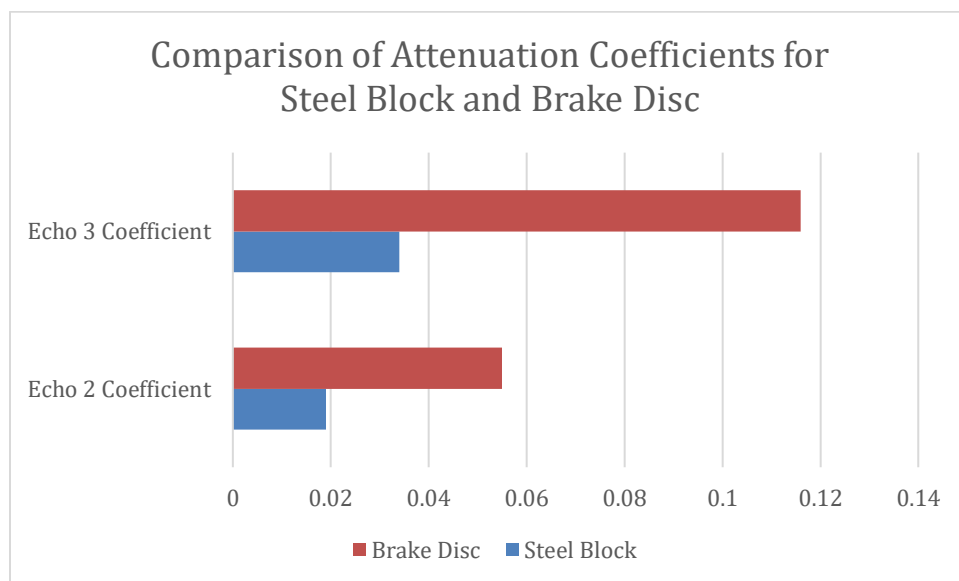


Figure 2: Comparison of Attenuation Coefficients for Steel Block and Brake Disc

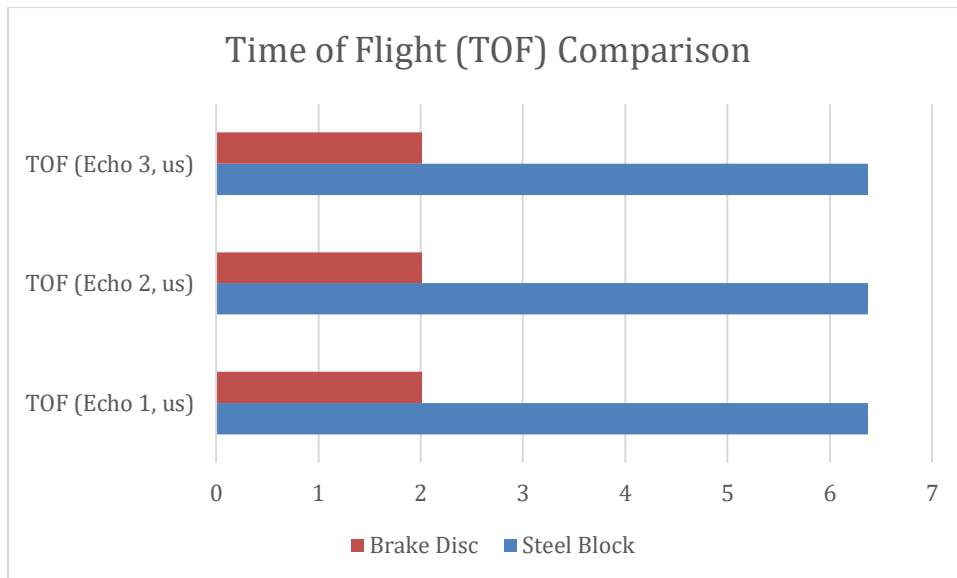


Figure 3: Average Time of Flight for Steel Block and Brake Disc

Part 2: Through Wall Sizing Accuracy Analysis

In evaluating through-wall sizing, significant fluctuations to the size estimation were observed concerning the operator. The regression analysis revealed that Operator 4 was the most precise with an R-squared of 0.993, a regression slope of 1.107, and negligible levels of regression bias. On the other hand, details of systematic bias were observed from some of the operators, such that they systematically under or overestimated the defect sizes, especially at the extremes.

MAE values used to clarify measurement precision differences between operators also provided the basis for formulating hypotheses. The variation was noted to be a result of differences in the level of expertise of the operators and how strictly they followed set procedures.

In general, the data prove the role of calibration and operators' training to be crucial. The results indicate that while accurate measurement can be obtained from ultrasonic equipment, consistent variation from the operators represents a major concern. Reducing these gaps through more adequate training and integration of guidelines would lead to more consistent and accurate defect size estimations, which enhance the use of ultrasonic for through-wall sizing for industrial applications.

Scatter Plot for Operator 4 (Most Accurate):

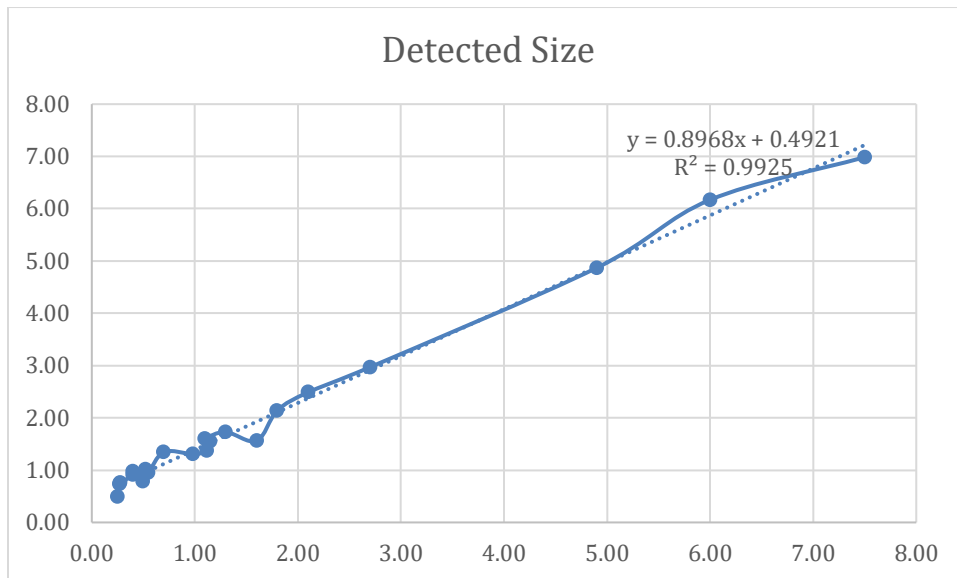


Figure 4: True Size vs. Detected Size for Operator 4

Scatter Plot for Least Accurate Operator:

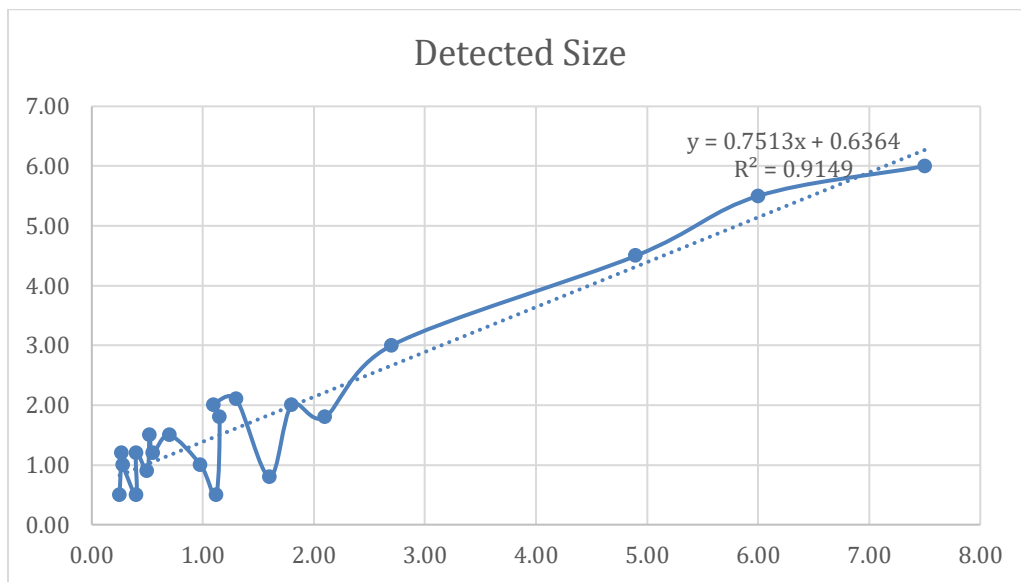


Figure 5: True Size vs. Detected Size for Operator X (Least Accurate Operator)

Mean Absolute Error (MAE) Across Operators:

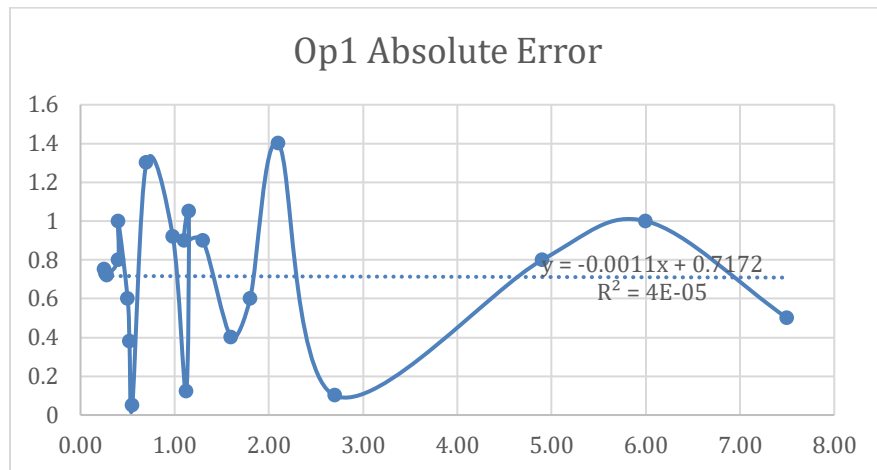


Figure 6: Mean Absolute Error for Op1

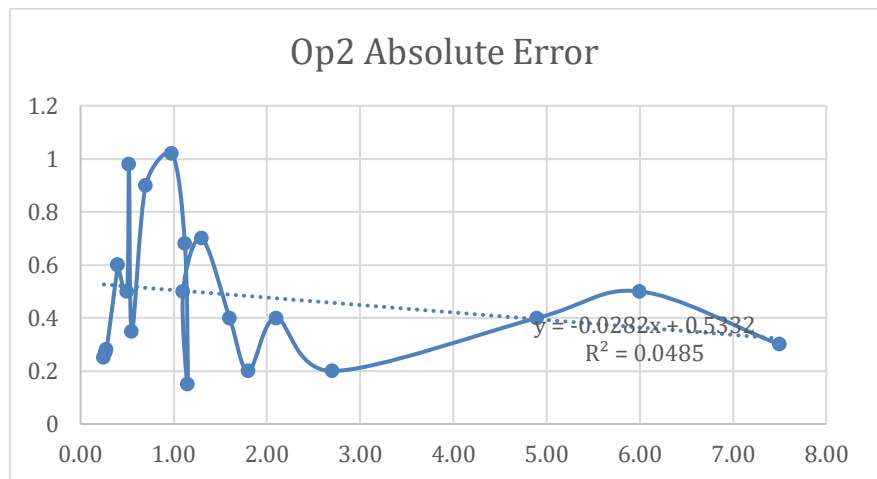


Figure 7: Mean Absolute Error for Op2

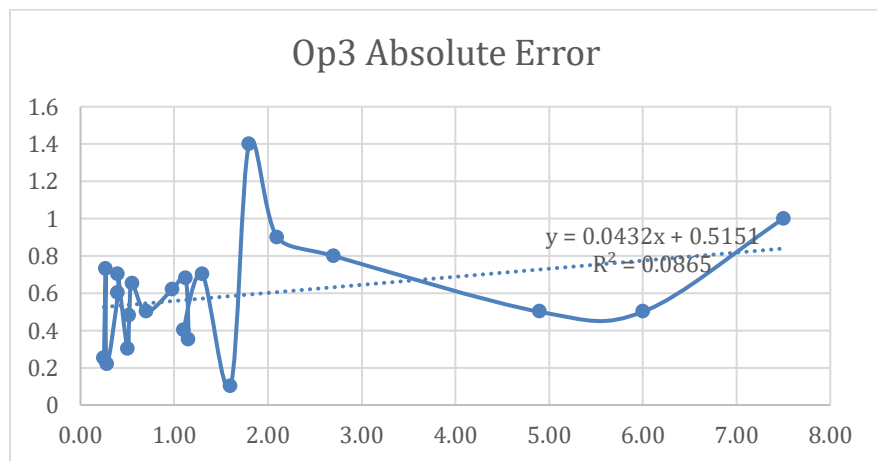


Figure 8: Mean Absolute Error for Op3

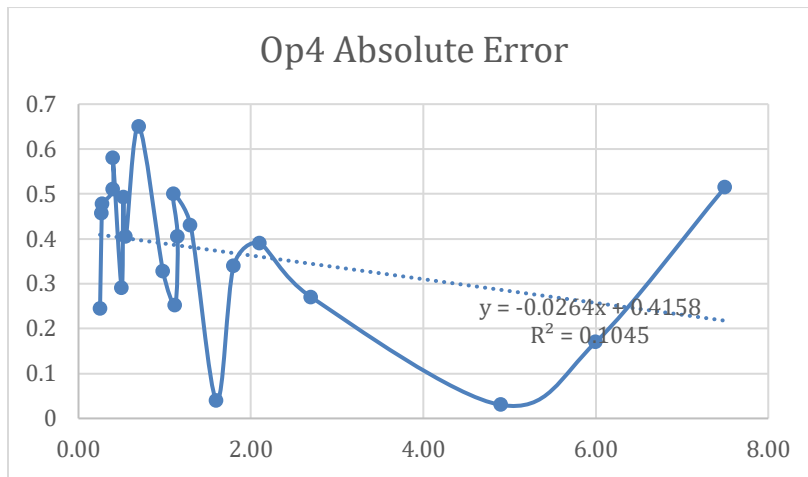


Figure 9: Mean Absolute Error for Op4

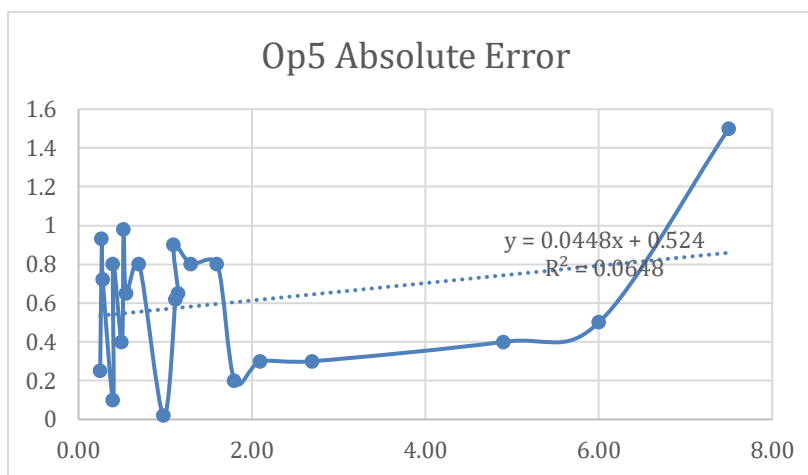


Figure 10: Mean Absolute Error for Op5

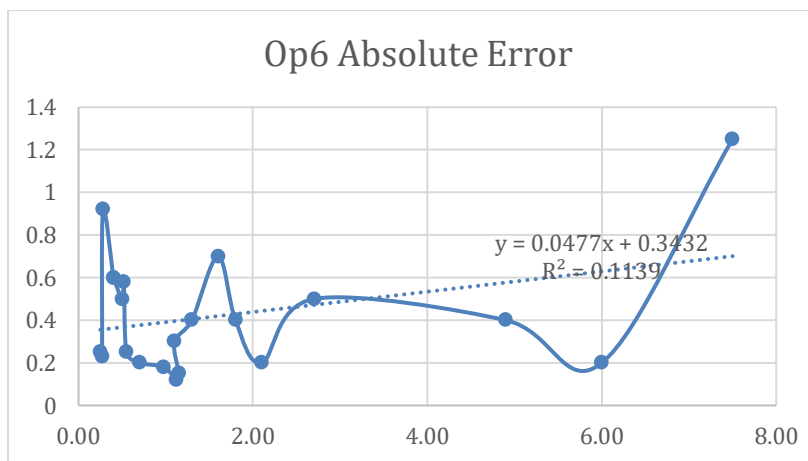


Figure 11: Mean Absolute Error for Op6

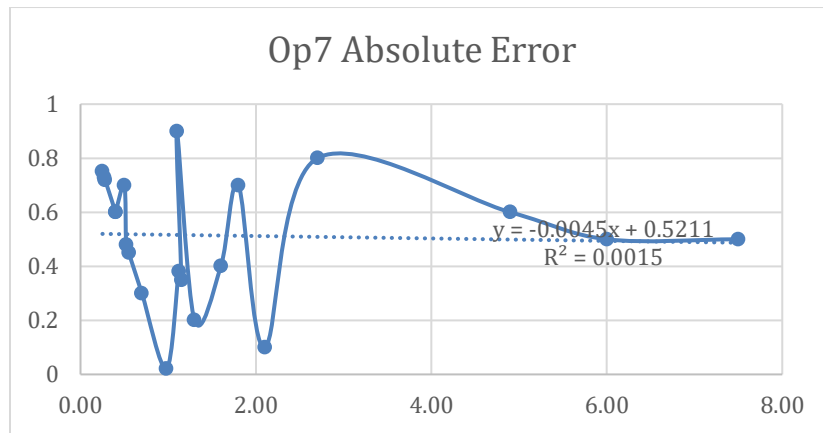


Figure 12: Mean Absolute Error for Op7

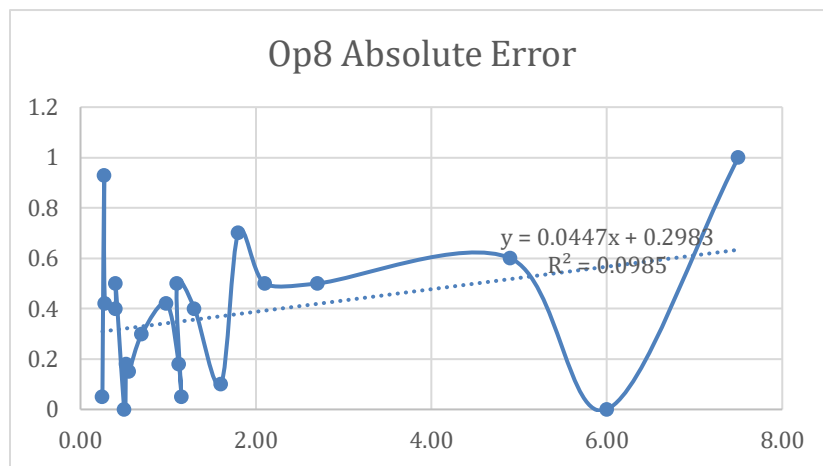


Figure 13: Mean Absolute Error for Op8

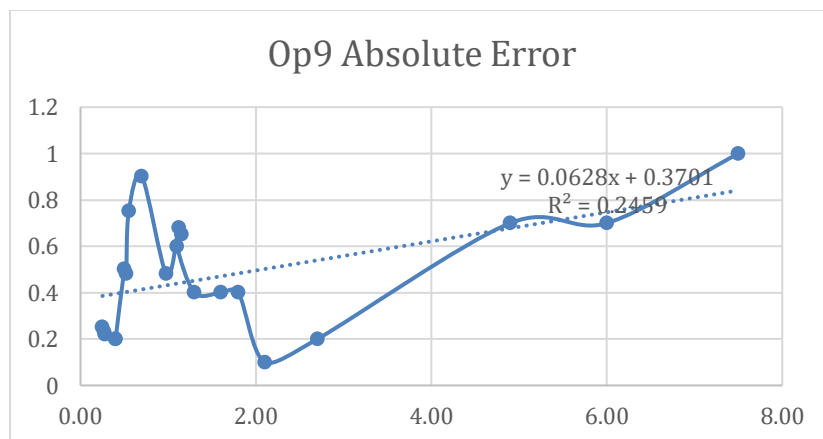


Figure 14: Mean Absolute Error for Op9

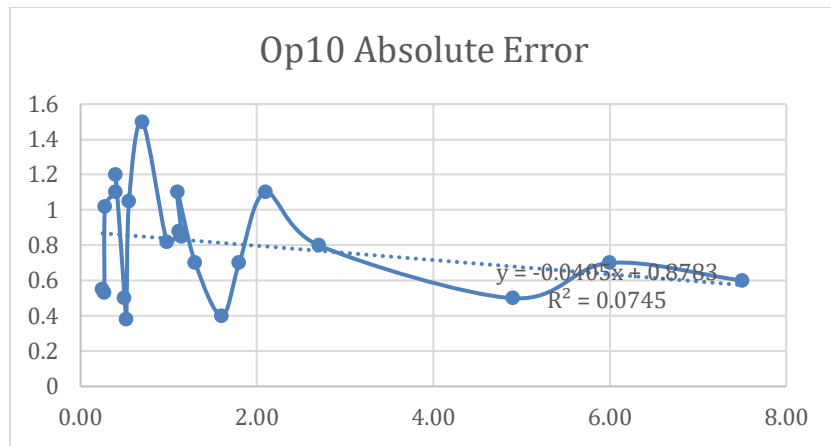


Figure 15: Mean Absolute Error for Op10

Discussion

Part 1: Meaning of Attenuation Coefficients for the Characterization of Material and Non-Destructive Testing Applications

Attenuation coefficients are among the key parameters associated with non-destructive testing, particularly ultrasonic testing, according to their relevance to identifying the capacity of the material to absorb and scatter sound waves. Contrasts in attenuation coefficients have been valuable to the probe in terms of structural composition and material types such as mild steel against brake disc material. Internal discontinuities are also likely, for example, as higher attenuation coefficients imply a higher tendency for internal discontinuities, or material degradation over an extended period. For NDT work, knowledge of these coefficients becomes fundamental in the accurate assessment of material integrity, prediction of lifetimes of components, and, above all, safety in critical industries such as aerospace, automotive, and manufacturing.

Part 2: Proficiency of the Procedure of Ultrasonic Thickness Gauging with Operator Performance Variation

The analysis of operator performance for the through-the-wall sizing exercise gives rise to measurement uncertainty, even under the same procedure and equipment. Such variability is a crucial concern in ensuring that results would prove consistent and robust with ultrasonic thickness gauging. Results indicate that inter-operator differences concerning accuracy-defining regression analysis metrics are another reflection of human problems such as technique, experience, and familiarity with the equipment. Equipment was reliable, and yet, on comparing results from one operator to another, there was a difference in results, thus indicating standardization in procedure would align to more consistent measurements.

Conclusion

The importance of UT in evaluating material integrity and ensuring the reliability of structures was evident in both the studies of this research work. Part One, entitled "Determination of Attenuation Coefficients for Mild Steel and Brake Disc Materials," has yielded knowledge about the properties that qualify these materials as such. The calculated attenuation coefficients demonstrated the big differences between the two materials and are expected to have a decisive impact on efficiency and accuracy in ultrasonic testing. These results contribute to a better understanding of how material composition affects the propagation of sound waves and, in the long run, the effectiveness of NDT methods to detect possible flaws.

Part 2 of the study analyzed ultrasonic thickness gauging to operator-to-operator measurement variations. The regression analysis indicated that operator performances differed from each other, confirming the significance of technique and equipment calibration continuity. The study also showed that, while the ultrasonic flaw detector can perform measurements reliably, many errors can usually be traced to the operator's ability coupled with compliance with standardized procedures. Therefore, further training and clearer protocols would remedy inconsistencies and promote more reliable measurements.

In conclusion, these findings lend credence to ultrasonic testing as a capable diagnostic tool in evaluating structural integrity wherein lay several venues for subsequent research. Further study using various materials and their corresponding attenuation measurements could help broaden the scope of the activities of ultrasonic testing.

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