

Attenuation Coefficient Analysis of a Steel block and Brake Disc (Part 1)

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Abstract

This report evaluates the attenuation coefficients of a mild steel block and a brake disc using ultrasonic time-of-flight methods with a 5 MHz probe. Amplitudes from three reflected echoes were measured, and attenuation coefficients were calculated using logarithmic decay equations. The steel block exhibited low and consistent attenuation, indicating uniformity and suitability for structural integrity applications. In contrast, the brake disc demonstrated higher and more variable attenuation, aligning with its functional role in energy dissipation. Confidence intervals further validated the reliability of the results, highlighting the significance of material properties in ultrasonic evaluation.

Introduction

This study explores the attenuation characteristics of a mild steel block and a brake disc using ultrasonic techniques to assess material properties. Ultrasonic waves attenuate as they propagate through materials due to energy absorption, which is quantified by the attenuation coefficient (α). By analysing attenuation coefficients, insights can be gained into material uniformity, density, and functionality.

Apparatus

1. Ultrasonic Flaw Detector:

- A calibrated D Scan 705 ultrasonic flaw detector capable of transmitting and receiving high-frequency sound waves was used.



FIGURE 1 ULTRASONIC FLAW DETECTOR

- A 5 MHz zero-degree probe ensured consistent measurements across both samples.

- Coupling Gel (Water)

2. Samples:

- **Mild Steel Block:** A rectangular block with thickness measurements of 19 mm.
- **Brake Disc:** A vented disc, with measurements taken from the 6 mm thick friction surface.

3. Measurement Setup:

- Time-of-flight (ToF) techniques measured echo amplitudes at various defect depths.
- Echo 1, Echo 2, and Echo 3 were recorded for each sample.

4. Statistical Tools:

- Calculations and graphs were performed using Microsoft Excel to evaluate attenuation coefficients.

Measurements and graphs of raw measurements

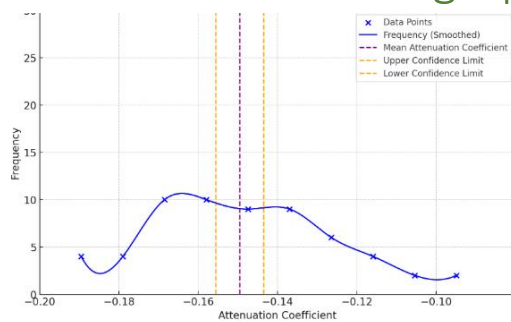


FIGURE 2 STEEL BLOCK

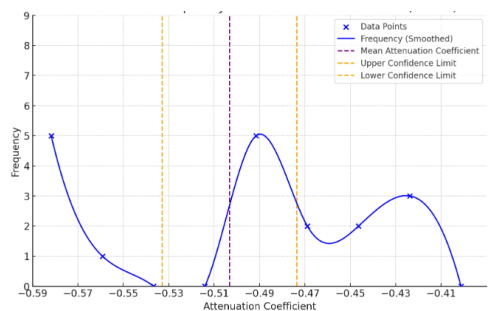


FIGURE 3 BRAKE DISC

Steel Block						
thickness: 19						
Measurement	(Echo 1)	(Echo 2)	(Echo 3)	$\alpha_{1,2}$	$\alpha_{2,3}$	$\alpha_{1,3}$
1	85	39	21	-0.178	-0.141	-0.16
2	74	35	20	-0.171	-0.128	-0.15
3	77	39	23	-0.155	-0.121	-0.138
4	94	47	25	-0.158	-0.144	-0.151
5	94	46	25	-0.163	-0.139	-0.151
6	86	42	25	-0.164	-0.119	-0.141
7	80	39	22	-0.164	-0.131	-0.148
8	76	35	21	-0.177	-0.117	-0.147
9	84	40	22	-0.17	-0.137	-0.153
10	76	35	21	-0.177	-0.117	-0.147
Measurement	(Echo 1)	(Echo 2)	(Echo 3)	$\alpha_{1,2}$	$\alpha_{2,3}$	$\alpha_{1,3}$
1	74	37	18	-0.158	-0.165	-0.162
2	68	29	17	-0.195	-0.122	-0.158
3	70	31	17	-0.186	-0.137	-0.162
4	68	32	20	-0.172	-0.107	-0.14
5	74	34	22	-0.178	-0.1	-0.139
6	70	30	17	-0.194	-0.13	-0.162
7	74	37	25	-0.158	-0.09	-0.124
8	59	28	16	-0.17	-0.128	-0.149
9	71	31	16	-0.189	-0.151	-0.17
10	74	35	22	-0.171	-0.106	-0.139

Brake Disc						
Measurement	(Echo 1)	(Echo 2)	(Echo 3)	$\alpha_{1,2}$	$\alpha_{2,3}$	$\alpha_{1,3}$
1	32	51	23	-0.427029419	-0.5764039	-0.502
2	84	39	21	-0.555357798	-0.44807552	-0.502
3	85	38	17	-0.582725548	-0.58222446	-0.582
4	88	49	25	-0.423810987	-0.48709345	-0.455
5	82	43	22	-0.467242328	-0.48507629	-0.476
6	84	47	21	-0.42030238	-0.58313094	-0.502

Steel Block			Brake disc		
Attenuation Coefficient Range	Frequency		Attenuation Coefficient Range	Frequency	
-0.194 to -0.18	4		-0.5331 to -0.5705	5	
-0.18 to -0.17	4		-0.5705 to -0.548	1	
-0.17 to -0.16	10		-0.548 to -0.5254	0	
-0.16 to -0.15	10		-0.5254 to -0.5028	0	
-0.15 to -0.14	9		-0.5028 to -0.4803	5	
-0.14 to -0.13	9		-0.4803 to -0.4577	2	
-0.13 to -0.12	6		-0.4577 to -0.4351	2	
-0.12 to -0.11	4		-0.4351 to -0.4126	3	
-0.11 to -0.1	2		-0.4126 to -0.39	0	
-0.1 to -0.089	2				

FIGURE 4 DATA SET

Calculations and Error Estimates

The attenuation of ultrasonic waves in a material can be described by the exponential decay equation:

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

Where:

- A: Amplitude of the wave after traveling a distance Z through the material.
- A0: Initial amplitude of the wave.
- α : Attenuation coefficient (dB/mm)
- z: Thickness or travel distance of the material.

This equation models how the amplitude of an ultrasonic wave decreases exponentially due to energy loss as it propagates through a medium.

Rearranged to find α (attenuation coefficient):

$$\alpha = \frac{(20 \cdot \log_{10} \frac{A}{A_0})}{z}$$

Physical Meaning

This formula indicates that:

- α : Represents the rate of energy loss per unit distance (dB/mm)

- The larger the value of α , the more energy the material absorbs, resulting in greater attenuation.

For both samples, amplitudes for three echoes were recorded, and attenuation coefficients were calculated for:

- $\alpha_{1,2}$: Between Echo 1 and Echo 2
- $\alpha_{2,3}$: Between Echo 2 and Echo 3
- $\alpha_{1,3}$: Between Echo 1 and Echo 3

Results and Discussion

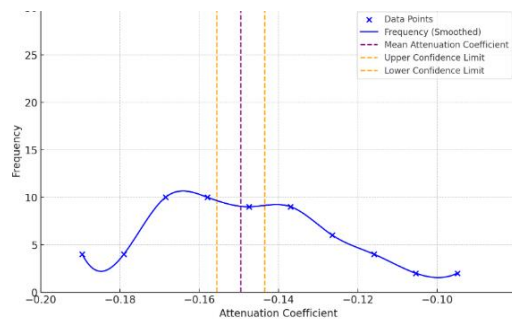


FIGURE 5 STEEL BLOCK

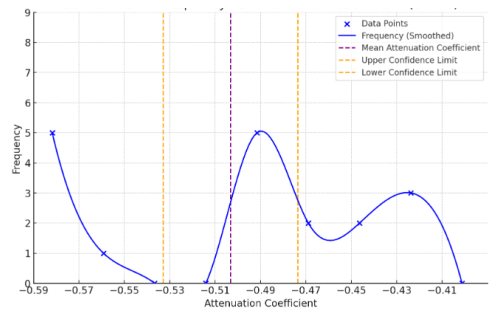


FIGURE 6 BRAKE DISC

Comparison of Samples

- **Steel Block:**
 - Exhibited consistent and low attenuation, indicating a dense and uniform material.
 - Suitable for applications requiring minimal energy loss and reliable structural integrity.
- **Brake Disc:**
 - Showed higher and more variable attenuation, reflecting a material with more internal energy absorption, possibly due to microstructural differences or porosity.
 - Higher attenuation aligns with the function of the brake disc, which prioritizes energy dissipation during braking.

Significance of the Bell Curve

Material Uniformity:

- The bell curve for the steel block reflects relatively consistent attenuation values, which is essential for applications requiring reliable wave propagation, such as structural integrity assessments.
- The tighter distribution confirms that the steel block's material is dense and uniform, making it ideal for transmitting ultrasonic waves with minimal energy loss.

Energy Dissipation in Brake Disc:

- The brake disc's wider bell curve highlights its material's capability to absorb and dissipate energy. This characteristic is critical for its function in braking systems.
- The shifted curve toward higher attenuation coefficients aligns with the expectation that brake discs prioritize energy absorption over wave transmission due to their role in heat dissipation.

Confidence in Results:

- The scatter plots, enhanced with 95% confidence intervals, provide visual confirmation of the reliability of the attenuation coefficient calculations.
- For the steel block, the confidence intervals are narrower, reflecting less variability in the data, while the brake disc's wider intervals indicate greater variability, emphasizing material heterogeneity.

Significance of 95% Confidence:

- The use of $1.96 \times \sigma$ (deviation) allows us to define a range within which we are 95% confident that a given attenuation value will fall. Confidence intervals can be defined

using Z value in the table in figure 6, which is a standardised commonly used table in standard deviation.

- This confidence interval is crucial for assessing reliability, especially when evaluating material consistency. Narrow intervals suggest precise, predictable behaviour (steel block), while wider intervals indicate more diverse material properties (brake disc).

Confidence Interval	Z
80%	1.282
85%	1.440
90%	1.645
95%	1.960
99%	2.576
99.5%	2.807
99.9%	3.291

FIGURE 7 CONFIDENCE INTERVAL TABLE

Conclusion

The analysis revealed distinct attenuation characteristics between the mild steel block and the brake disc. The steel block demonstrated low and consistent attenuation coefficients, indicative of a uniform and dense material ideal for reliable ultrasonic wave propagation. Conversely, the brake disc exhibited higher and more variable attenuation coefficients, reflecting its heterogeneous structure designed for energy absorption during braking.

The use of 95% confidence intervals validated the consistency and variability of the results, with narrower intervals for the steel block indicating greater material predictability and wider intervals for the brake disc highlighting functional heterogeneity.

Appendix

ISO/DIS 16809(en)

Non-destructive testing — Ultrasonic thickness determination

<https://www.iso.org/obp/ui/en/#iso:std:iso:16809:dis:ed-3:v1:en>

D Scan 705:

https://www.silverwingme.com/ultrasonic_flaw_detector/dscan_ultrasonic_flaw_detector.html

Confidence Interval Table: <https://www.alchemer.com/resources/blog/how-to-calculate-confidence-intervals/>

Images



FIGURE 8 BRAKE DISC USED IN EXPERIMENT



FIGURE 9 MILD STEEL BLOCK WITH 5MHZ PROBE DURING THE EXPERIMENT

*Ultrasonic Attenuation Coefficient Determination and
Probability of Sizing Analysis (Part 2)*

James Brady

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Through Wall Sizing Accuracy Analysis

Abstract

This report evaluates the performance of ultrasonic thickness gauging conducted by 10 operators across 21 defect specimens. Operator performance was assessed using a range of metrics, including slope, intercept, coefficient of determination (R^2), mean error, mean absolute error, and probability of detection (PoD). Top-performing operators demonstrated strong accuracy, minimal bias, and consistent defect detection, evidenced by high R^2 values, slopes near 1, low intercepts, and perfect PoD. Conversely, lower-ranked operators exhibited significant systematic biases and variability in defect sizing. The integration of metrics like mean absolute error and PoD provide an insight into operator reliability, highlighting areas for improvement in training and equipment calibration. These findings offer valuable insights into the reliability and consistency of ultrasonic gauging techniques for defect detection and sizing.

Introduction/Methodology

Ultrasonic thickness gauging is a non-destructive testing (NDT) method widely used for evaluating material integrity and defect sizing. This technique relies on transmitting high-frequency sound waves into a material using an ultrasonic gauging device and analysing the echoes returned from internal features to determine thickness. Accurate and consistent measurements are essential for ensuring structural safety and reliability in engineering applications.

This study evaluates the performance of 10 operators using ultrasonic gauging to measure defect sizes across 21 samples. The analysis focuses on key metrics such as slope, intercept, and R^2 from regression models, along with error and absolute error calculations, to assess both accuracy and consistency.

Apparatus

Ultrasonic thickness gauging equipment:

The ultrasonic gauging device operates by transmitting high-frequency sound waves into a material and measuring the time taken for the echoes to return from internal features or the opposite surface. The thickness is calculated based on the speed of sound in the material.

Defect specimens with known true sizes

- Twenty-one defect samples with true sizes ranging from 0.25 mm to 7.5 mm were prepared and verified for accuracy prior to testing.
- These specimens provide a controlled environment for assessing operator performance and gauging equipment reliability.

Statistical tools for regression and error analysis

- Statistical software (Microsoft Excel) was employed to perform linear regression, compute metrics such as slope, intercept, and R^2 , and analyse error distributions.
- Measurement limits were calculated to assess the reliability and variability of operator measurements.

Visualization software for graphing results

- Graphs, including scatter plots, error trends, and operator rankings, were generated to illustrate performance metrics.
- Visualization tools were used to overlay true size lines, trendlines, and measurement limits for clarity.

Objective:

The objective of this study was to assess operator performance of a new ultrasonic thickness gauging technique. Measurements were compared against known defect sizes to evaluate the following:

Analysis:

Linear Regression analysis was performed to compute the slope (m), intercept (c), and Coefficient of Determination (R^2) for each operator. Linear regression is a statistical technique used to model the linear

relationship between a dependent variable and one or more independent variables. (Bogdan et al. (2015) Krider et al., 2013; Walker & Ort, 2015; Marini et al., 2022).

Mean error (ME) and mean absolute error (MAE) across all defects were calculated to assess individual performance trends.

Mean Error and Mean Absolute Error: - ME provides information about the overall bias or systematic error in the measurements or predictions. An ME close to 0 indicates that the measurements or predictions are unbiased, while a non-zero ME suggests the presence of systematic errors. MAE is a measure of the average absolute difference between the measured/predicted and actual values, providing information about the overall accuracy (Tian et al., 2022; Truong et al., 2021; Hamid et al., 2023; Naeem et al., 2021; AL-Salihi & AL-Ramahy, 2017). Absolute error is important for understanding the magnitude of the errors, and provides a direct measure of the deviation from the true or expected value. (Tomala et al., 2017; Torriani-Pasin et al., 2013).

Relevance of Metrics:

1. **Slope:**

- The slope of the regression line between the measured and actual thickness values indicates the accuracy of the thickness gauging technique (Veilleux et al., 2016).
- A slope close to 1 suggests that the thickness measurements are accurate and unbiased (Veilleux et al., 2016).

2. **Intercept:**

What the Intercept Represents:

- The intercept is the point where the regression line crosses the y-axis (measured size when the true size is zero).
- A positive intercept indicates a tendency to oversize defects.
- An intercept close to **0** suggests minimal bias, meaning the operator is not consistently adding or subtracting a baseline value from the true defect size.
- A negative intercept would indicate an under sizing bias (though no negative intercepts are present in this case)

The intercept of the regression line represents the systematic bias in the thickness measurements (Veilleux et al., 2016). An intercept close to 0 indicates that there is minimal systematic bias in the thickness measurements (Veilleux et al., 2016).

3. Coefficient of Determination (R^2):

- R^2 is a measure of the goodness-of-fit of the regression model, representing the proportion of the variance in the measured thickness that is explained by the actual thickness (Veilleux et al., 2016; Sousan et al., 2016).
- - R^2 ranges from 0 to 1, where 0 indicates that the model explains none of the variability of the response data around its mean, and 1 indicates that the model explains all the variability of the response data around its mean (Krider et al., 2013; Marini et al., 2022).
- A higher R^2 value (closer to 1) indicates a better fit of the model and higher reliability of the thickness gauging technique (Veilleux et al., 2016; Sousan et al., 2016).

4.) Probability of Detection:

Probability of Detection (PoD) is a metric for evaluating an operator's ability to identify defects consistently. A PoD value of 1 signifies flawless detection of all defects, while values below 1 indicate missed detections. The table below highlights the PoD performance for each operator.

5.) Measurement Limits (Graphs)

Measurements were analysed, with measurement limits (± 0.5 mm, ± 1.0 mm) placed in relation to the operators trendline. These limits establish acceptable ranges for measurements, indicating whether a measurement deviates significantly from the true size. Measurements within ± 0.5 mm are considered highly accurate, while those within ± 1.0 mm are acceptable but may require further scrutiny. Deviations beyond ± 1.0 mm highlight significant operator or equipment issues.

The measurement limits were placed on the trendline rather than the true line to better reflect operator-specific performance. The trendline accounts for systematic biases (e.g., slope and intercept deviations), making it a more accurate representation of how consistently operators performed relative to their measurement patterns. This approach isolates variability specific to each operator and highlights outliers without being skewed by deviations from the ideal benchmark. While the true line assesses absolute accuracy, the trendline-based limits are more appropriate for evaluating consistency and identifying performance trends within the context of the operators' actual results.

Results and Discussion

Slope:

- **High Slope Values (> 1):**
 - There are no operators with slopes greater than 1 in this dataset, indicating no over-sizing tendencies.
- **Low Slope Values (< 1):**
 - **Op3 (0.81)** and **Op9 (0.82)** exhibit a tendency to **underestimate** defect sizes consistently.
 - Slopes less than 1 reflect a bias toward under-sizing across the range of defects, particularly for larger ones.
- **Slope Values Close to 1:**
 - Operators such as **Op1 (1.00)**, **Op7 (0.99)**, and **Op4 (0.90)** demonstrate strong accuracy, with slopes indicating minimal deviation from the ideal proportional relationship between measured and true sizes.

Comparison and Significance:

- **High Accuracy Operators:**
 - Operators with slopes closest to 1, such as **Op1**, **Op7**, and **Op4**, show proportional accuracy and reliable measurements.
- **Lower Performing Operators:**
 - Operators like **Op3** and **Op9**, with slopes well below 1, highlight consistent under-sizing tendencies, which may compromise reliability.

Intercept:

- **High Intercept Values (> 0.6):**
 - **Op1 (0.70)**, **Op3 (0.72)**, and **Op10 (0.97)** have the highest intercepts, indicating a stronger tendency to **overestimate defect sizes** systematically across the range of measurements.
 - For **Op3**, the combination of a high intercept and a slope significantly less than 1 suggests a pattern of overestimating smaller defects while underestimating larger ones.
- **Low Intercept Values (< 0.4):**
 - **Op6 (0.32 mm)**, **Op9 (0.32)**, and **Op8 (0.33)** exhibit minimal systematic bias, with intercepts closer to zero.
 - Operators such as **Op4 (0.49)** and **Op7 (0.51)** also show relatively low intercept values, correlating with strong R^2 values and consistent performance.

Comparison and Significance:

- **High Accuracy Operators:**
 - Operators with lower intercept values, such as **Op6**, **Op9**, and **Op8**, demonstrate minimal systematic bias, aligning with their strong performance metrics.
- **Lower Performing Operators:**
 - Operators with higher intercept values, such as **Op10**, **Op1**, and **Op3**, tend to add a baseline offset to their measurements, which can negatively impact accuracy.

R²:

- **High R² Values (> 0.98):**
 - **Op4 (0.99)** and **Op7 (0.98)** exhibit exceptional consistency, with measurements closely aligned to the regression line.
 - High R² values indicate minimal variability and high reliability in the operator's performance.
- **Moderate R² Values (0.93 – 0.96):**
 - Operators such as **Op6 (0.94)** and **Op8 (0.95)** show moderate variability in their measurements but maintain strong overall reliability.
 - Lower R² values indicate occasional outliers or inconsistencies in performance.

Comparison and Significance:

- **Consistent Operators:**
 - Operators with the highest R² values, such as **Op4** and **Op7**, provide highly reliable measurements with minimal variability, showcasing exceptional consistency.
- **Inconsistent Operators:**
 - Operators such as **Op5 (0.91)**, with a relatively lower R² value, demonstrate greater variability in their measurements, reducing confidence in their results.

Probability of Detection:

Top Performers (PoD = 1.0):

- Operators **Op1**, **Op3**, **Op4**, **Op5**, **Op7**, **Op8**, and **Op10** achieved a perfect PoD of 1.0, indicating detection of all defects.

- These operators demonstrate consistent detection capabilities across all defect sizes, aligning with their generally strong performance metrics in other areas such as slope and R^2 .

2. **Moderate Performers (PoD < 1.0):**

- **Op6** and **Op9** achieved PoD values of 0.95, missing one or two defects during the evaluation. These operators may face challenges detecting smaller or more subtle defects.
- **Op2** recorded the lowest PoD at 0.86, reflecting several missed detections. This operator likely struggled with smaller defect sizes, which aligns with lower performance metrics in slope and R^2 .

Impact of Missed Detections

1. **Smaller Defects:**

- Missed detections are often associated with smaller defects (<0.5 mm), where signal strength or noise can obscure detection.
- **Op2**, with the lowest PoD, may benefit from additional training or equipment calibration to improve sensitivity to small defects.

2. **Consistency vs. Detection:**

- While PoD evaluates detection capability, it does not address the accuracy of defect sizing. For example, an operator with a perfect PoD but poor slope or R^2 may detect defects but fail to size them accurately.

Comparison to Other Metrics

1. **High PoD and Accuracy:**

- Operators with a perfect PoD, such as **Op4** and **Op7**, also exhibit strong performance in R^2 and slope, reflecting both accurate defect detection and consistent sizing.

2. **Low PoD and Performance Gaps:**

- Operators **Op6** and **Op9**, with lower PoD values (0.95), align with their mid-tier rankings in slope and R^2 . These operators may benefit from targeted feedback to address gaps in detection consistency.

3. **Op2 Performance:**

- With the lowest PoD (0.86), **Op2** exhibits significant detection challenges, reinforcing its lower overall performance ranking. This operator may require additional training or calibration to improve defect identification.

Mean Error and Mean Absolute Error:

High Mean Error Operators (Higher Bias):

- Op1 (0.70 mm) and Op10 (0.75 mm) exhibit the highest mean errors, indicating a strong tendency to overestimate defect sizes.
- These values suggest systematic over-sizing across defect sizes, correlating with their higher intercept values.

Low Mean Error Operators (Minimal Bias):

- **Op6 (0.07 mm)** and **Op9 (0.01 mm)** exhibit the lowest mean errors, indicating minimal directional bias in their measurements.

High Mean Absolute Error Operators (Inconsistent Performance):

- **Op10 (0.81 mm)** and **Op1 (0.72 mm)** have the highest mean absolute errors, suggesting significant inconsistencies in their defect measurements, even though the errors may not always be in the same direction.
- This high absolute error indicates that these operators are less reliable, even if their mean error shows a tendency toward over-sizing.

3. Low Mean Absolute Error Operators (Consistent Performance):

- **Op4 (0.37 mm)** and **Op8 (0.38 mm)** demonstrate the lowest mean absolute errors, indicating high consistency in their measurements.
- This aligns with their strong performance in other metrics, such as R^2 and slope, showcasing their ability to deliver accurate and reliable results.

Comparison of Mean Error and Mean Absolute Error

- **Operators with Minimal Bias and Low Inconsistencies:**
 - **Op4 (Mean Error: 0.32 mm, Mean Absolute Error: 0.37 mm)** and **Op8 (Mean Error: 0.14 mm, Mean Absolute Error: 0.38 mm)** strike a strong balance between accuracy and consistency, making them top performers in this category.
- **Operators with High Bias but Moderate Consistency:**

- **Op1 (Mean Error: 0.70 mm, Mean Absolute Error: 0.72 mm) and Op10 (Mean Error: 0.75 mm, Mean Absolute Error: 0.81 mm)** demonstrate both high bias and variability, indicating a need for significant improvement in measurement accuracy.
- **Operators with Low Bias but Moderate Inconsistencies:**
 - **Op9 (Mean Error: 0.01 mm, Mean Absolute Error: 0.48 mm) and Op6 (Mean Error: 0.07 mm, Mean Absolute Error: 0.43 mm)** show minimal bias but moderate inconsistency, suggesting room for improvement in overall reliability.

Final Ranking:

1. Top Performers:

- **Op4:**
 - With a strong slope (0.90), low intercept (0.49 mm), the highest R^2 (0.99), a perfect PoD (1.00), and the lowest **Mean Absolute Error** (0.37 mm), Op4 ranks as the most consistent, accurate, and reliable operator overall.
 - The combination of minimal bias, high consistency, and reliable defect detection highlights this operator's excellence in both defect sizing and detection.
- **Op7:**
 - A slope near 1 (0.99), low intercept (0.51 mm), high R^2 (0.98), and perfect PoD (1.00) make Op7 a strong performer.
 - Despite a slightly higher **Mean Absolute Error** (0.51 mm) than Op4, its consistently accurate sizing and flawless defect detection capability place it among the top-ranked operators.

2. Mid-Tier Performers:

- **Op8:**
 - Demonstrates solid accuracy with a slope of 0.90 and low intercept (0.33 mm). It maintains a perfect PoD (1.00) and a relatively low **Mean Absolute Error** (0.38 mm).
 - However, its slightly lower R^2 (0.95) and moderate variability in defect sizing prevent it from reaching the top tier.
- **Op6:**
 - Achieves a moderate slope (0.85), minimal intercept bias (0.32 mm), and a PoD of 0.95. Its **Mean Error** (0.07 mm) is among the lowest, indicating minimal directional bias.

- However, its **Mean Absolute Error** (0.43 mm) suggests some variability in performance, particularly for larger defects where under-sizing tendencies are more apparent.
- **Op9:**
 - Similar to Op6, with a slope of 0.82, intercept of 0.32 mm, and PoD of 0.95. While it has the lowest **Mean Error** (0.01 mm), its **Mean Absolute Error** (0.48 mm) highlights moderate inconsistencies in sizing.
 - Consistent under-sizing tendencies and missed detections prevent Op9 from reaching the top tier.

3. Lower Performers:

- **Op3:**
 - Exhibits a low slope (0.81), high intercept (0.72 mm), and moderate R^2 (0.95), reflecting consistent under-sizing and systematic overestimation of smaller defects.
 - Despite a perfect PoD (1.00), its relatively high **Mean Absolute Error** (0.59 mm) highlights significant variability in defect sizing, reducing its reliability.
- **Op10:**
 - While maintaining a reasonable slope (0.87) and R^2 (0.96), the high intercept (0.97 mm) and the highest **Mean Absolute Error** (0.81 mm) indicate significant systematic over-sizing and overall inconsistency.
 - Its perfect PoD (1.00) suggests strong defect detection ability but fails to mitigate its inaccuracies in defect sizing

Graphs:

Intercept:

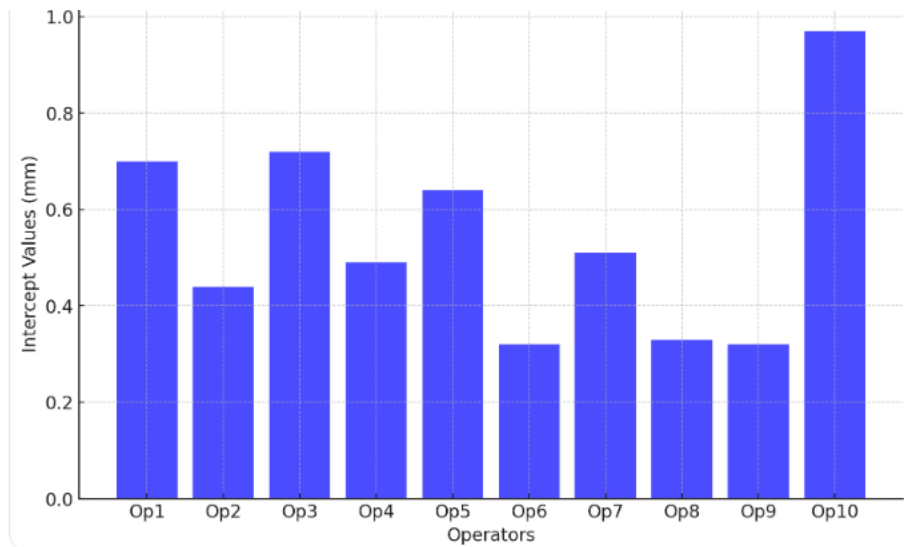


FIGURE 10 INTERCEPT VALUES FOR EACH OPERATOR, HIGHLIGHTING THEIR SYSTEMATIC BIAS IN DEFECT SIZE MEASUREMENTS. LOWER INTERCEPT VALUES SHOW MINIMAL BIAS.

Slope:

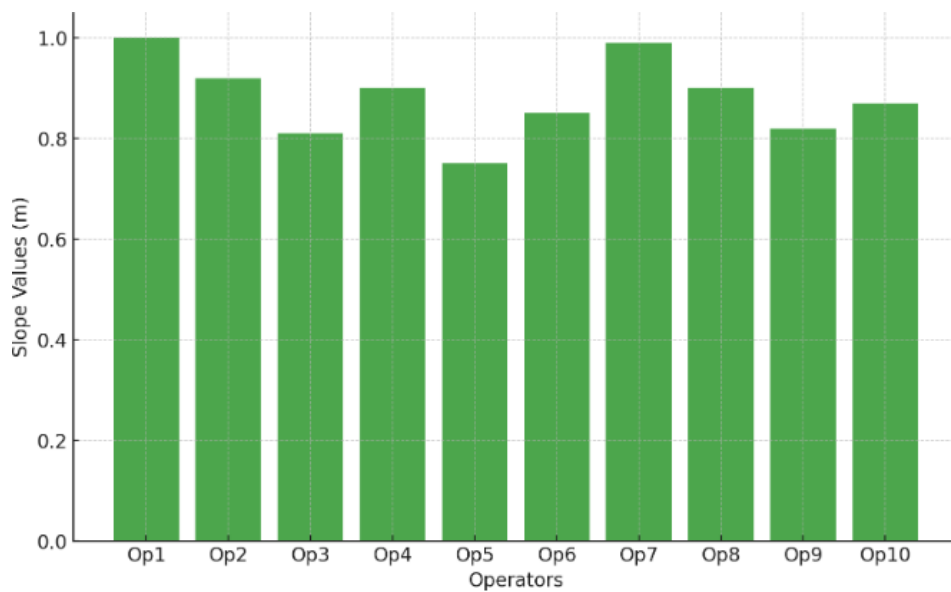


FIGURE 11 SLOPE VALUES: HIGHLIGHTING THE DEGREE OF ACCURACY IN THE MEASUREMENTS. A SLOPE CLOSE TO 1 INDICATES HIGH ACCURACY.

R^2 :

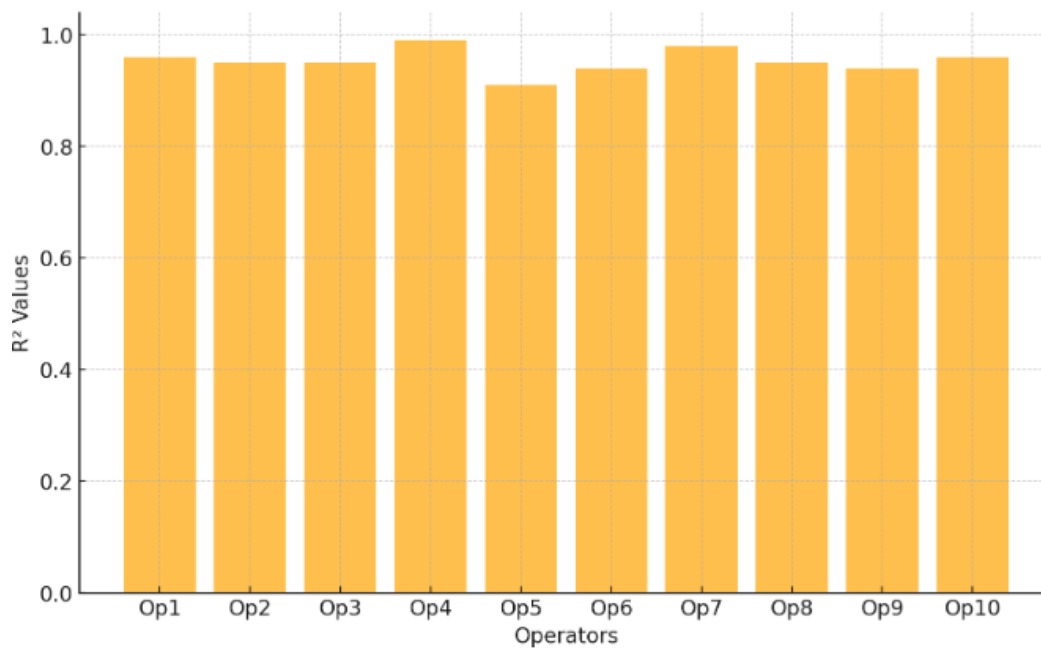


FIGURE 12 R² VALUES: REPRESENTING THE CONSISTENCY AND RELIABILITY OF MEASUREMENTS. HIGHER VALUES (CLOSER TO 1) INDICATE GREATER RELIABILITY.

Mean Error:

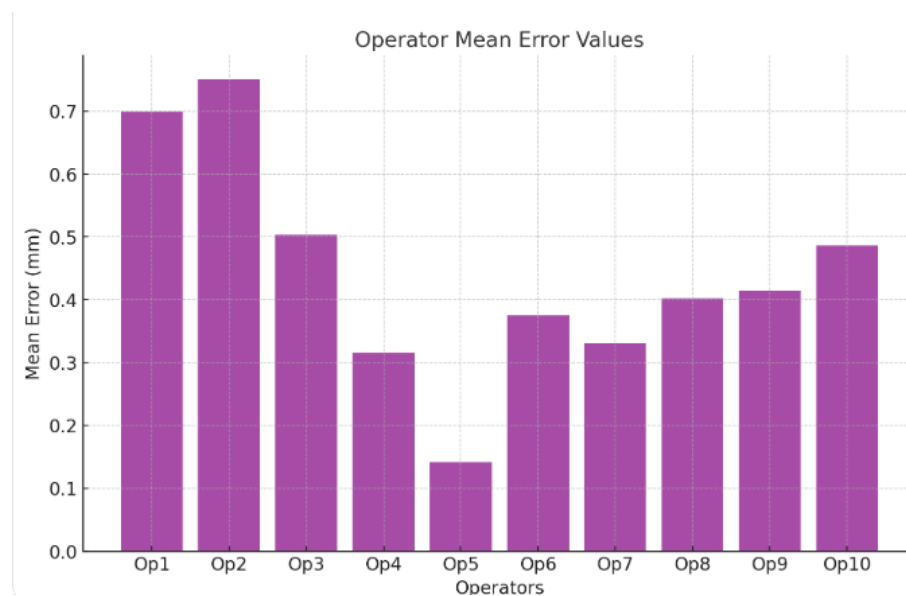


FIGURE 13 MEAN ERROR VALUES: SHOWING THE AVERAGE SIGNED DEVIATION OF MEASUREMENTS FROM THE TRUE DEFECT SIZES. POSITIVE OR NEGATIVE VALUES INDICATE OVER-SIZING OR UNDER-SIZING TRENDS, RESPECTIVELY.

Mean Absolute Error:

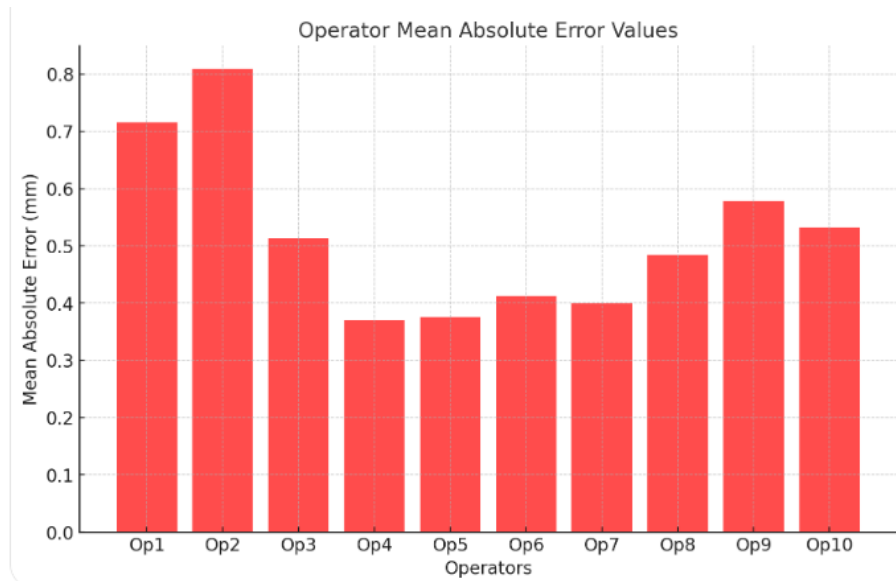


FIGURE 14 MEAN ABSOLUTE ERROR VALUES: HIGHLIGHTING THE AVERAGE MAGNITUDE OF DEVIATION REGARDLESS OF DIRECTION, REPRESENTING OVERALL MEASUREMENT CONSISTENCY.

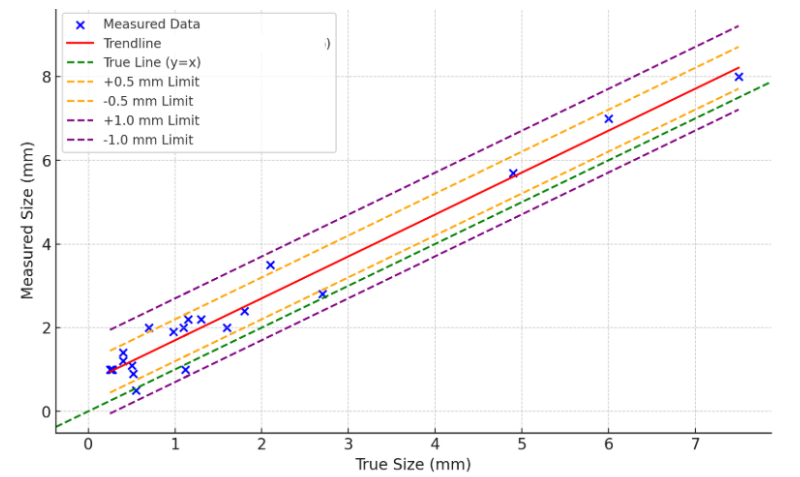


FIGURE 15 OP1 GRAPH

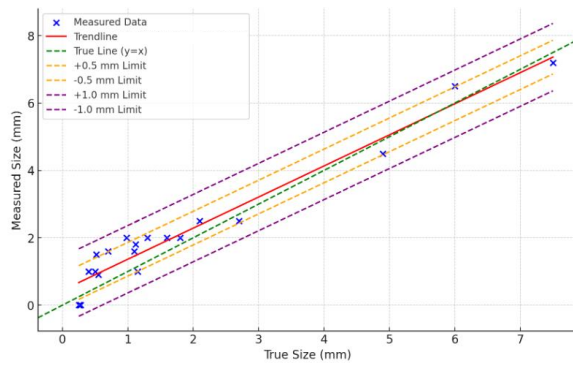


FIGURE 16 OP2 GRAPH

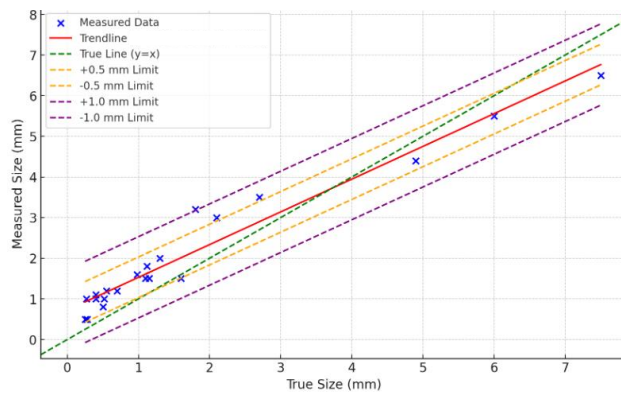


FIGURE 17 OP3 GRAPH

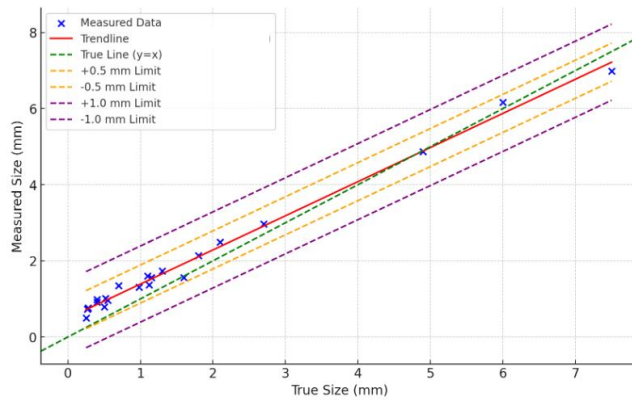


FIGURE 18 OP4 GRAPH

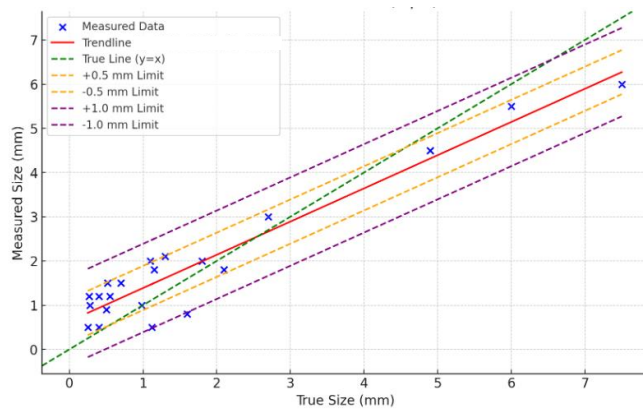


FIGURE 19 OP5 GRAPH

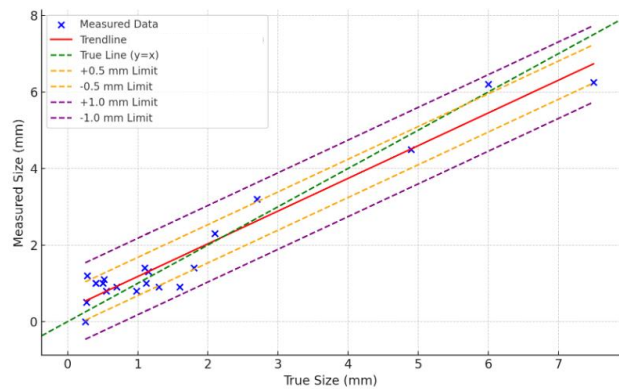


FIGURE 20 OP6 GRAPH

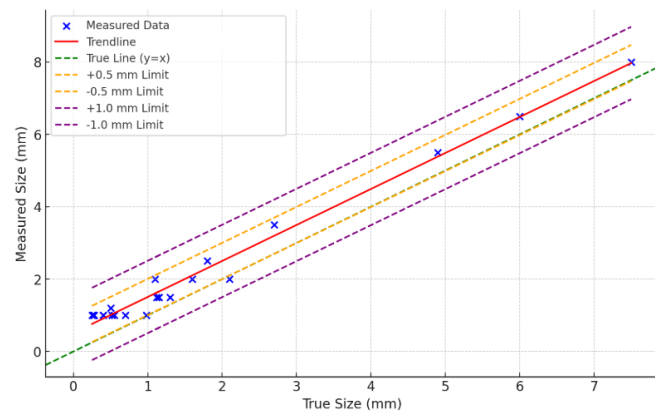


FIGURE 21 OP7 GRAPH

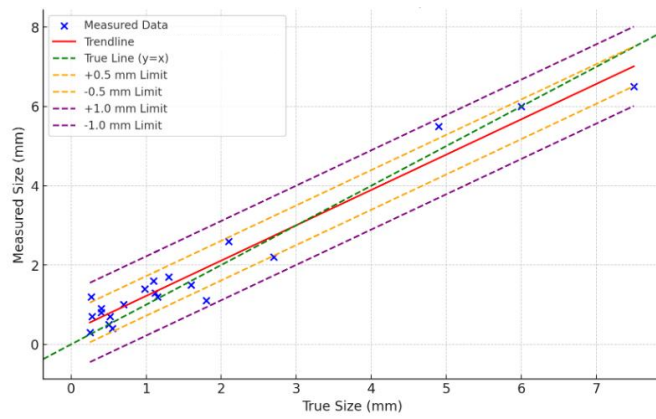


FIGURE 22 OP8 GRAPH

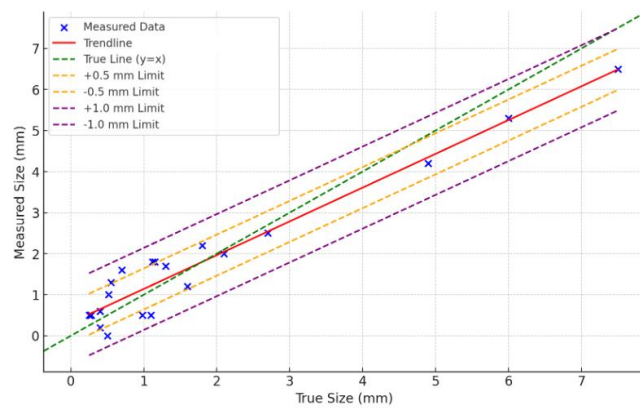


FIGURE 23 OP9 GRAPH

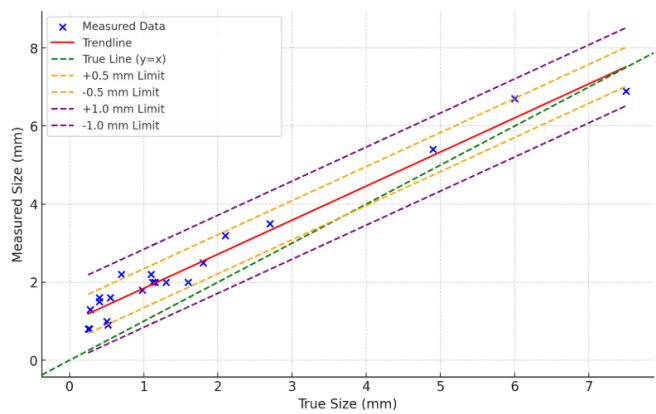


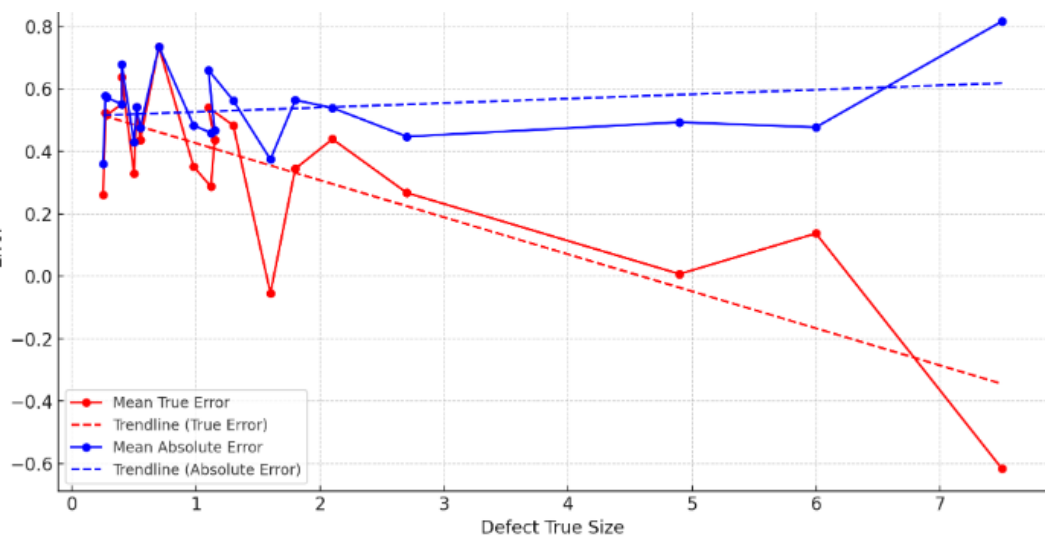
FIGURE 24 OP10 GRAPH

Equation Values Table

Operator	Slope (m)	Intercept (c)	R ²
Op1	1	0.7	0.96
Op2	0.92	0.44	0.95
Op3	0.81	0.72	0.95
Op4	0.9	0.49	0.99
Op5	0.75	0.64	0.91
Op6	0.85	0.32	0.94
Op7	0.99	0.51	0.98
Op8	0.9	0.33	0.95
Op9	0.82	0.32	0.94
Op10	0.87	0.97	0.96

Combined Error and Absolute Error Graph

A line graph compares the true error and absolute error for each defect across operators.



Trendline Analysis

- True Error:
 - A steep negative slope in the trendline confirms that larger defects are often underestimated.
- Absolute Error:
 - A slightly positive slope suggests that the magnitude of errors increases for larger defects, highlighting the need for equipment recalibration or enhanced protocols for large defects.

Conclusion:

Overall, this analysis highlights the value of combining performance metrics such as slope, intercept, R^2 , mean error, and PoD to provide a comprehensive evaluation of operator performance. High-performing operators exhibit balanced strengths across all metrics, while lower-performing operators demonstrate specific areas for improvement. These findings demonstrate the importance of ongoing training, feedback, and equipment calibration to enhance the reliability and consistency of ultrasonic gauging techniques, ensuring accurate defect detection and sizing in critical applications.

Appendix

Veilleux, M., Lapointe, N., Webber, D., Binder, T., Blanchfield, P., Cruz-Font, L., ... & Cooke, S. (2016). Pressure sensor calibrations of acoustic telemetry transmitters. *Animal Biotelemetry*, 4(1). <https://doi.org/10.1186/s40317-015-0093-0>

Krider, L., Magner, J., Perry, J., Vondracek, B., & Ferrington, L. (2013). Air-water temperature relationships in the trout streams of southeastern minnesota's carbonate-sandstone landscape. *Jawra Journal of the American Water Resources Association*, 49(4), 896-907. <https://doi.org/10.1111/jawr.12046>

Marini, C., Sisti, D., Sarzynski, M., Bouchard, C., Amatori, S., Rocchi, M., ... & Lucertini, F. (2022). Effect of individual characteristics and aerobic training on the %hrr-%vo2r relationship. *European Journal of Sport Science*, 23(8), 1600-1611. <https://doi.org/10.1080/17461391.2022.2113441>

Bogdan, M., Berg, E., Sabatti, C., Su, W., & Candès, E. (2015). Slope—adaptive variable selection via convex optimization. *The Annals of Applied Statistics*, 9(3). <https://doi.org/10.1214/15-aos842>

Walker, B. and Ort, D. (2015). Improved method for measuring the apparent co2 photocompensation point resolves the impact of multiple internal conductances to co2 to net gas exchange. *Plant Cell & Environment*, 38(11), 2462-2474. <https://doi.org/10.1111/pce.12562>

Tian, W., Cao, X., & Peng, K. (2022). Technology for position correction of satellite precipitation and contributions to error reduction—a case of the '720' rainstorm in henan, china. *Sensors*, 22(15), 5583. <https://doi.org/10.3390/s22155583>

Truong, N., Ngo, N., & Pham, A. (2021). Forecasting time-series energy data in buildings using an additive artificial intelligence model for improving energy efficiency. *Computational Intelligence and Neuroscience*, 2021(1). <https://doi.org/10.1155/2021/6028573>

Hamid, A. A. K. A., Nawi, W. I. A. W. M., Lola, M. S., Mustafa, W. A., Malik, S. M. A., Zakaria, S., ... & Abdullah, M. T. (2023). Improvement of time forecasting models using machine learning for future pandemic applications based on covid-19 data 2020–2022. *Diagnostics*, 13(6), 1121. <https://doi.org/10.3390/diagnostics13061121>

Naeem, M., Yu, J., Aamir, M., Khan, S. A., Adeleye, O., & Khan, Z. (2021). Comparative analysis of machine learning approaches to analyze and predict the covid-19 outbreak. *PeerJ Computer Science*, 7, e746. <https://doi.org/10.7717/peerj-cs.746>

AL-Salihi, A. M. and AL-Ramahy, Z. A. (2017). A neural network model for estimation soil temperature bases on limited meteorological parameters in selected provinces in iraq. *Journal of Applied and Advanced Research*, 292-300. <https://doi.org/10.21839/jaar.2017.v2i5.106>

Tomala, J., Pokonieczny, K., Mościcka, A., & Wilbik, A. (2017). Travel time map of szczecin main railway station. *Proceedings of 10th International Conference "Environmental Engineering"*. <https://doi.org/10.3846/enviro.2017.149>

Torriani-Pasin, C., Bonuzzi, G. M. G., Soares, M. A. A., Antunes, G. L., Palma, G. C. S., Monteiro, C. B. d. M., ... & Corrêa, U. C. (2013). Performance of down syndrome subjects during a coincident timing task. *International Archives of Medicine*, 6(1), 15. <https://doi.org/10.1186/1755-7682-6-15>

Data:

Operator	Slope (m)	Intercept (c)	R ²	Mean Error	Mean Absolute Error	Combined Mean Error	Operator	Probability of Detection
Op1	1	0.7	0.96	0.7	0.72	0.71	Op1	1
Op2	0.92	0.44	0.95	0.31	0.48	0.4	Op2	0.86
Op3	0.81	0.72	0.95	0.39	0.59	0.49	Op3	1
Op4	0.9	0.49	0.99	0.32	0.37	0.34	Op4	1
Op5	0.75	0.64	0.91	0.21	0.6	0.4	Op5	1
Op6	0.85	0.32	0.94	0.07	0.43	0.25	Op6	0.95
Op7	0.99	0.51	0.98	0.5	0.51	0.5	Op7	1
Op8	0.89	0.33	0.95	0.14	0.38	0.26	Op8	1
Op9	0.82	0.32	0.94	0.01	0.48	0.24	Op9	0.95
Op10	0.87	0.97	0.96	0.75	0.81	0.78	Op10	1