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# **Ultrasonic Attenuation Coefficient Determination and Probability of Sizing Analysis**

Structural Integrity and Material Evaluation (ACEB7013)

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*Figure 1: The importance of Material investigation (Iatrakis, 2022).*

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|       |                                                     |    |
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## 2 Abstract

The following technical paper encompasses the Determination of The attenuation Coefficient of Two samples, a Mild Steel block, and an Aluminium Adapter plate. Attenuation measurements have been conducted by the author using a Digital Ultrasonic Flaw Detector. These measurements have then been used to calculate the attenuation coefficients.

For the second part of this paper, a data set of Through Wall Size measurements has been provided for analysis. The data set consists of 21 defects, with increasing size, 10 operators have each measured all of the defects once.

Linear regression and statistical analysis methods have been used to analyse the sizing accuracy of the operators, equipment and procedure. Results showed a significant difference in accuracy between operators, showing a 158% difference in accuracy between most and least accurate operator. The large variation in accuracy between operators, indicates improvement in the method of certain operators is necessary.

The analysis also showed a relationship between the defect size and overall accuracy of the measurements. The measurements at small defects sizes were highly inaccurate (213% Relative Accuracy Error). With accuracy dropping to -8% at the largest defect size. Indicating a accuracy problem with equipment at small defect sizes.

### 3 Part 1: Ultrasonic Coefficient Determination

The following part shows the measurement and calculation of the Attenuation coefficient of two material samples. With measurements carried out in the science lab at the UWTSD IQ campus.

Figure 2 shows the used material samples. A mild steel rectangular block and an aluminium adapter plate.

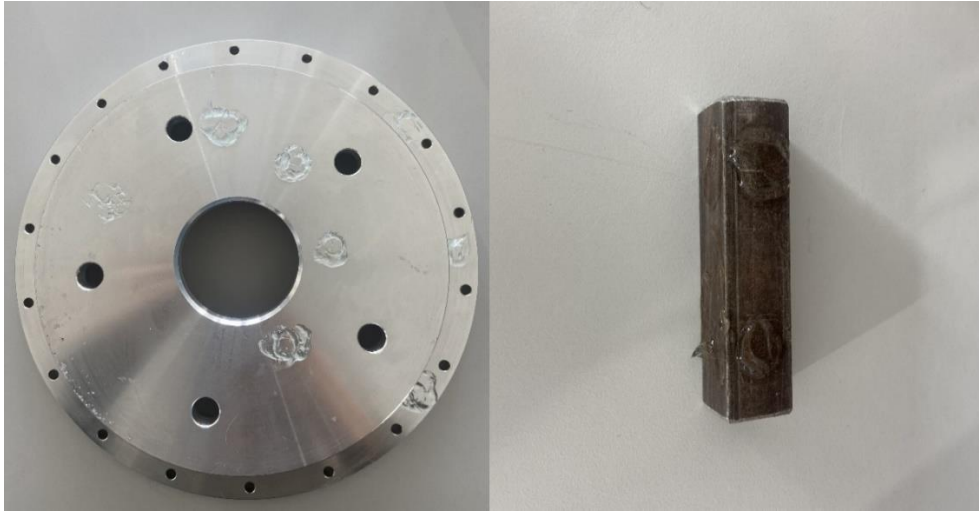


*Figure 2: Used Material Samples (Iatrakis, 2023)*

#### 3.1 Apparatus

A Silverwing D-Scan 705 Digital ultrasonic flaw detector [1] with a zero-degree 5MHz probe has been used for measuring (Figure 3). The measurements have been executed at room temperature in a science lab. A hair gel has been used as a couplant to aid sound energy transfer into the test specimen to ensure a usable ultrasonic signal can be obtained [2].

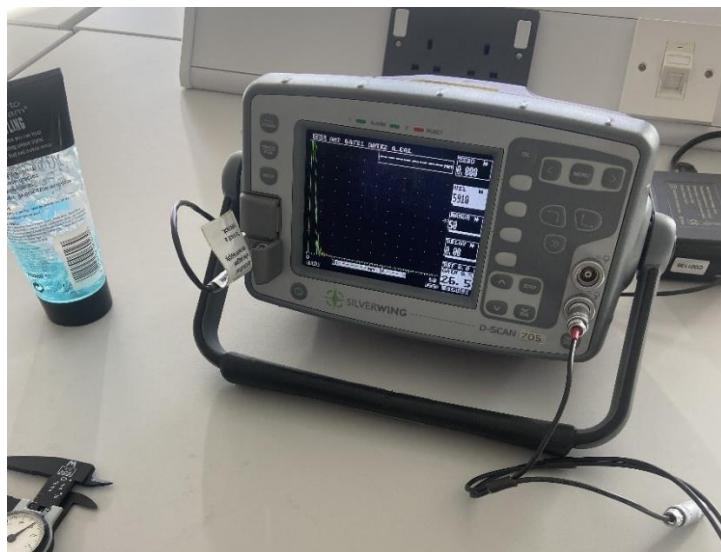


*Figure 3: D-Scan 705 Ultrasonic Flaw Detector (Iatrakis, 2023)*

## 3.2 Introduction

### ***Attenuation***

Traditionally, the study of sound propagation assumed ideal materials, where sound pressure reduction was solely due to wave spreading. Source 5 However, in real materials, sound weakens due to two mechanisms: scattering and absorption. Both are encompassed by the term "attenuation," reflecting the overall sound energy reduction [3].

Absorption primarily causes energy loss, affecting transmitted energy and echoes from flaws. To counter this, one can increase voltage or use lower frequencies with lower absorption.

Scattering is more complex, diminishing echo height and creating multiple echoes with varying transit times, known as "grass." Increasing voltage doesn't effectively mitigate scattering. Lower frequencies are essential for detecting small flaws, despite limitations like reduced sound beaming and longer pulses. (Source 4)source 6

### ***Attenuation Coefficient***

The attenuation coefficient is a quantitative measure of the loss of ultrasound energy caused by transmission within a medium [3]

### ***Use of attenuation coefficient***

Attenuation coefficients serve as pivotal indicators in non-destructive testing, particularly in ultrasonic testing within engineering applications. These coefficients quantify the rate at which ultrasonic waves lose energy as they traverse different materials. The change in attenuation coefficients becomes especially significant in flaw detection; deviations from expected values can signal the presence of defects or irregularities within the material [4], [5].

Beyond engineering, the medical field extensively utilizes attenuation coefficients for diagnostic purposes. In medicine, changes in the attenuation coefficients of tissues and organs provide critical information about health conditions. For instance, alterations in the attenuation coefficient of biological tissues may indicate inflammation, tumours, or other pathological changes [5], [6]. This understanding of attenuation not only enhances non-destructive testing methodologies in engineering disciplines but also underlines its profound implications in medical diagnostics, where the assessment of attenuation coefficients is instrumental in detecting and diagnosing various diseases and health conditions.

### 3.3 Method & Measurements

#### **Method**

The mild steel block was measured in two axis on three positions for each axis. Two measurements on the outer ring and two measurements on the inner ring of the aluminium adapter plate were carried out. The magnitude of three consecutive pulse peaks were noted in order to determine the attenuation coefficient from this data.

Table 1 shows the results from the measurements. The displayed values describe the percentage of the screen range to which the peaks reach.

*Table 1: Raw Measurements (Iatrakis, 2023)*

|                                        |                                  |
|----------------------------------------|----------------------------------|
| <b>Sample:</b>                         | Mild Steel Rectangular Block (%) |
| <b>Thickness in testing axis (mm):</b> | 19.5                             |

| Measurement Position | Pulse Magnitude (%) |        |        |
|----------------------|---------------------|--------|--------|
|                      | Echo 1              | Echo 2 | Echo 3 |
| Left End             | 88                  | 42     | 20     |
| Middle               | 85                  | 42     | 22     |
| Right End            | 86                  | 42     | 20     |
| <b>AVERAGE</b>       | 86.33               | 42.00  | 20.67  |

|                                        |                              |
|----------------------------------------|------------------------------|
| <b>Sample:</b>                         | Mild Steel Rectangular Block |
| <b>Thickness in testing axis (mm):</b> | 18.9                         |

| Measurement Position | Pulse Magnitude (%) |        |        |
|----------------------|---------------------|--------|--------|
|                      | Echo 1              | Echo 2 | Echo 3 |
| Left End             | 80                  | 39     | 18     |
| Middle               | 82                  | 39     | 24     |
| Right End            | 79                  | 38     | 20     |
| <b>AVERAGE</b>       | 80.33               | 38.67  | 20.67  |

|                                        |                         |
|----------------------------------------|-------------------------|
| <b>Sample:</b>                         | Aluminium adapter plate |
| <b>Thickness in testing axis (mm):</b> | 13                      |

| Measurement Position | Pulse Magnitude (%) |        |        |
|----------------------|---------------------|--------|--------|
|                      | Echo 1              | Echo 2 | Echo 3 |
| Measurement 1        | 98                  | 41     | 18     |
| Measurement 2        | 98                  | 43     | 19     |
| Measurement 3        | 96                  | 42     | 20     |
| Measurement 4        | 97                  | 43     | 21     |
| <b>AVERAGE</b>       | 97.25               | 42.25  | 19.50  |

### 3.4 Calculations

The method of calculating the attenuation coefficient depends on the measurement method. Microsoft Excel has been used for the calculation. Figure 4 [3] shows arrangements for attenuation measurements on the basis of multiple echo consequences.

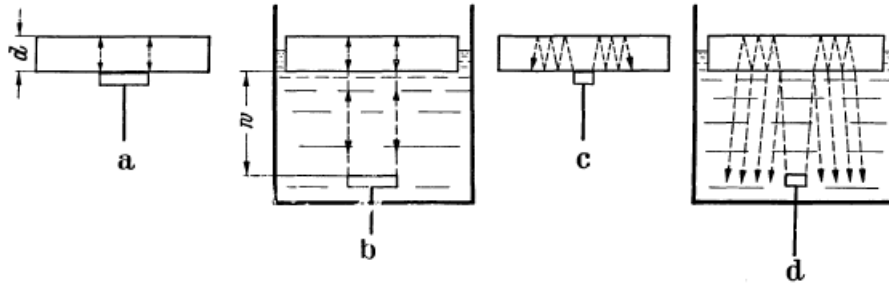


Figure 4: Arrangement for attenuation measurements on the basis of multiple echo consequences. (a) Direct contact, near-field; (b) delay line, near-field; (c) direct contact; (d) delay line, far field.

Since Method A is used, the formula for measuring the coefficient of attenuation  $\alpha$  in dB/mm is:

$$EQ\ 1: \alpha = \frac{1}{2d} S_E \text{ (dB/mm)} [3]$$

Where:

$\alpha$  is the attenuation coefficient in dB/mm

$d$  is the plate thickness in mm

$S_E$  is the ratio of two successive echo amplitudes measured in decibels:

$$EQ\ 2: S_E = 20 \log \left( \frac{A_0}{A_1} \right) \text{ (dB)}$$

Where:

$A_0$  is the amplitude of the initial ultrasonic pulse

$A_1$  is the amplitude of the second considered ultrasonic pulse

the "20 log" term in the formula is a conversion factor that transforms the ratio of amplitudes into a logarithmic scale in decibels [7], [8].

Combining the Equation 1 & 2, gives the complete formula to calculate the attenuation coefficient  $\alpha$ :

$$EQ\ 3: \alpha = \frac{1}{2d} 20 \log \left( \frac{A_0}{A_1} \right) \text{ (dB/mm)}$$

### 3.5 Error Estimates and Results

Using Equation 3 and the obtained measurement results (table 1), attenuation coefficient values for both samples have been determined.

Table 2 shows the results for the investigated samples. No further analysis of the samples is carried out with the attenuation coefficients. An expected value is unknown, hence, calculating the accuracy is not possible. A precision error percentage has been calculated to evaluate measurement [9].

Generally, a 10% precision error is accepted, two measurements in the second measurement of the Mild steel block and two of the aluminium adapter plate measurements are above this. This shows most measurements are of accepted precision. The outliers are expected to be due to the method of obtaining the Pulse magnitude, which had to be estimated from the small screen on the Ultrasonic Flaw Detector (Figure 3), which poses a limitation in the used method. A proposed solution would be to connect the apparatus to a pc and use software to obtain the precise magnitude of the pulses [1].

*Table 2: Calculated Results*

|                                        |                              |
|----------------------------------------|------------------------------|
| <b>Sample:</b>                         | Mild Steel Rectangular Block |
| <b>Thickness in testing axis (mm):</b> | 19.5                         |

| Measurement Position | Pulse Magnitude (%) |        |        | Attenuation Coefficient (dB/mm) |              |              | Precision Error (%) |       |       |
|----------------------|---------------------|--------|--------|---------------------------------|--------------|--------------|---------------------|-------|-------|
|                      | Echo 1              | Echo 2 | Echo 3 | $\alpha$ 1-2                    | $\alpha$ 1-3 | $\alpha$ 2-3 | % 1-2               | % 1-3 | % 2-3 |
| Left End             | 88                  | 42     | 20     | -0.165                          | -0.165       | -0.165       | 0.153               | 0.306 | 0.153 |
| Middle               | 85                  | 42     | 22     | -0.157                          | -0.151       | -0.144       | 4.226               | 8.635 | 4.413 |
| Right End            | 86                  | 42     | 20     | -0.160                          | -0.162       | -0.165       | 1.747               | 3.464 | 1.717 |
| <b>AVERAGE</b>       | 86.33               | 42.00  | 20.67  | -0.160                          | -0.159       | -0.158       | 0.794               | 1.595 | 0.800 |

|                                        |                              |
|----------------------------------------|------------------------------|
| <b>Sample:</b>                         | Mild Steel Rectangular Block |
| <b>Thickness in testing axis (mm):</b> | 18.9                         |

| Measurement Position | Pulse Magnitude (%) |        |        | Attenuation Coefficient (dB/mm) |              |              | Precision Error (%) |        |        |
|----------------------|---------------------|--------|--------|---------------------------------|--------------|--------------|---------------------|--------|--------|
|                      | Echo 1              | Echo 2 | Echo 3 | $\alpha$ 1-2                    | $\alpha$ 1-3 | $\alpha$ 2-3 | % 1-2               | % 1-3  | % 2-3  |
| Left End             | 80                  | 39     | 18     | -0.165                          | -0.171       | -0.178       | 3.737               | 7.337  | 3.603  |
| Middle               | 82                  | 39     | 24     | -0.171                          | -0.141       | -0.112       | 18.980              | 41.940 | 23.426 |
| Right End            | 79                  | 38     | 20     | -0.168                          | -0.158       | -0.147       | 6.344               | 13.104 | 6.774  |
| <b>AVERAGE</b>       | 80.33               | 38.67  | 20.67  | -0.168                          | -0.156       | -0.144       | 7.429               | 15.431 | 8.025  |

|                                        |                         |
|----------------------------------------|-------------------------|
| <b>Sample:</b>                         | Aluminium adapter plate |
| <b>Thickness in testing axis (mm):</b> | 13                      |

| Measurement Position | Pulse Magnitude (%) |        |        | Attenuation Coefficient (dB/mm) |              |              | Precision Error (%) |        |       |
|----------------------|---------------------|--------|--------|---------------------------------|--------------|--------------|---------------------|--------|-------|
|                      | Echo 1              | Echo 2 | Echo 3 | $\alpha$ 1-2                    | $\alpha$ 1-3 | $\alpha$ 2-3 | % 1-2               | % 1-3  | % 2-3 |
| Measurement 1        | 98                  | 41     | 18     | -0.291                          | -0.283       | -0.275       | 2.804               | 5.688  | 2.885 |
| Measurement 2        | 98                  | 43     | 19     | -0.275                          | -0.274       | -0.273       | 0.426               | 0.854  | 0.428 |
| Measurement 3        | 96                  | 42     | 20     | -0.276                          | -0.262       | -0.248       | 5.260               | 10.805 | 5.552 |
| Measurement 4        | 97                  | 43     | 21     | -0.272                          | -0.256       | -0.239       | 6.134               | 12.656 | 6.535 |
| <b>AVERAGE</b>       | 97.25               | 42.25  | 19.50  | -0.279                          | -0.268       | -0.258       | 3.695               | 7.529  | 3.837 |

## 4 Part 2: Through Wall Sizing Accuracy Analysis

The following parts encompass the analysis of a datasheet that's been provided to the author by Dr. Peter Charlton. The dataset consists of measurements conducted by 10 technicians, who have measured the size of 21 Defects, the true sizes of the defects have been provided.

Microsoft Excel and SPSS (IBM SPSS Statistics Version 27) software have been used for the analysis of the following.

### 4.1 Introduction

In the following part of this paper, statistical analysis and linear regression methods, were used to assess the accuracy of the operators, equipment and procedure. Linear regression has been used to model the relationship between the accuracy of different operators and the true size. Different statistical methods were used to determine the accuracies

### 4.2 Raw Data

The provided data consists of data measured by 10 technicians, of which each have measured the size of 21 Through Wall Thickness defects. Table 3 shows the raw data as provided.

*Table 3: Provided Through Wall Measurements*

| 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 |

### 4.3 Limitations

Small sample size: A low amount of measurements was provided, showing a high inconsistency throughout the measurements, both in between defect sizes and the different operators, increasing difficulty of statistical analysis. However, sources have suggested the minimal sample size for linear regression is required to be 8, which has been met in this study [10].

Assumption of linear regression: Linear regression analysis was conducted for this research under the condition that the assumptions of linear regression were met. These assumptions include linearity, independence, homoscedasticity, normality[11].

Type 1 and 2 errors: The statistical significance of the relationship was tested through hypothesis testing. It has to be noted that in statistics, the decision to reject the null hypothesis can never be 100% sure. When the H0 (Null Hypothesis) is rejected, but is true, this is a type I error and is at the largest equal to the significance level. On the other hand, when not rejecting the H0 falsely, it is a type II error. This phenomenon should be kept in mind when reporting statistical significant results [12], [13].

### 4.4 Linear Regression Analysis

To assess the sizing accuracy of the individual technicians, as well as the equipment and procedure, linear regression and statistical analysis have been used. Two research questions have been used to formulate a null, and alternative hypothesis. SPSS has been used for the Linear Regression Analysis.

#### 4.4.1 Regression Analysis 1

Research Question 1: How does the defect size affect the measurement accuracy?

A linear regression model was predicted for the different defect sizes and their measurements:

$$Y_i = \beta_0 + \beta_1 X_i + \epsilon_i$$

Where:

$Y_i$  (Dependent variable) is the measurement made by operator  $i$ .

$X_i$  (Independent variable) is the true size corresponding to the measurement

$\beta_0$  is the intercept (the expected measurement when the true size is zero).

$\beta_1$  is the slope (the change in measurement for a one-unit change in true size).

$\epsilon_i$  is the error term (captures unobserved factors affecting the measurement).

Linear regression provides estimates for coefficients, e.g the slope and intercept that quantify the relationship between the independent variable (defect size) and the dependent variable (measurement accuracy). The slope coefficient in the linear

regression model represents the measurement accuracy change for a one-unit defect size change.

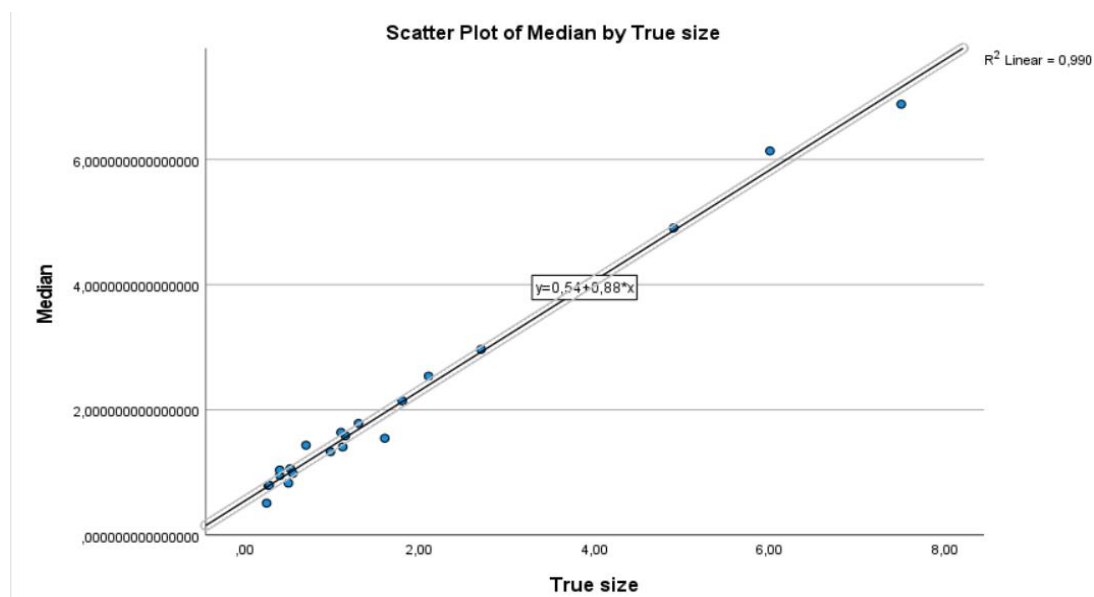
When applying linear regression analysis using SPSS, the following regression model has been computed:

$$Y_i = 0.881x + 0.544$$

This suggests that for every one-unit increase in defect size, the measurement accuracy is expected to increase by approximately 0.881.

The positive regression coefficient suggests that as the defect size increases, the measurement accuracy is expected to increase.

Graph 1 and table 5 show the regression analysis returned by SPSS.

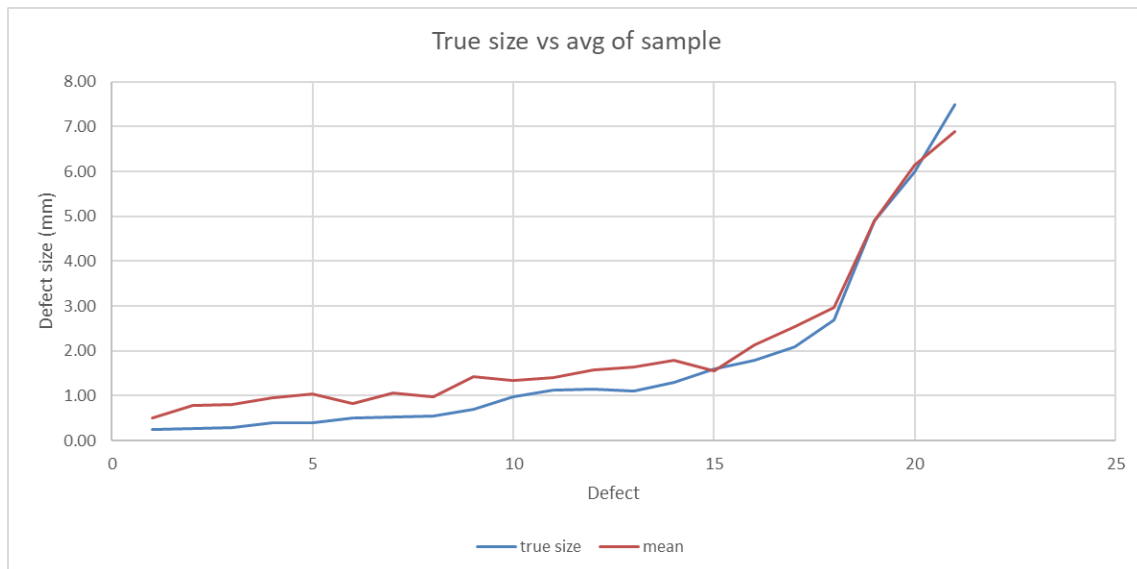


Graph 1: Regression Analysis Trendline

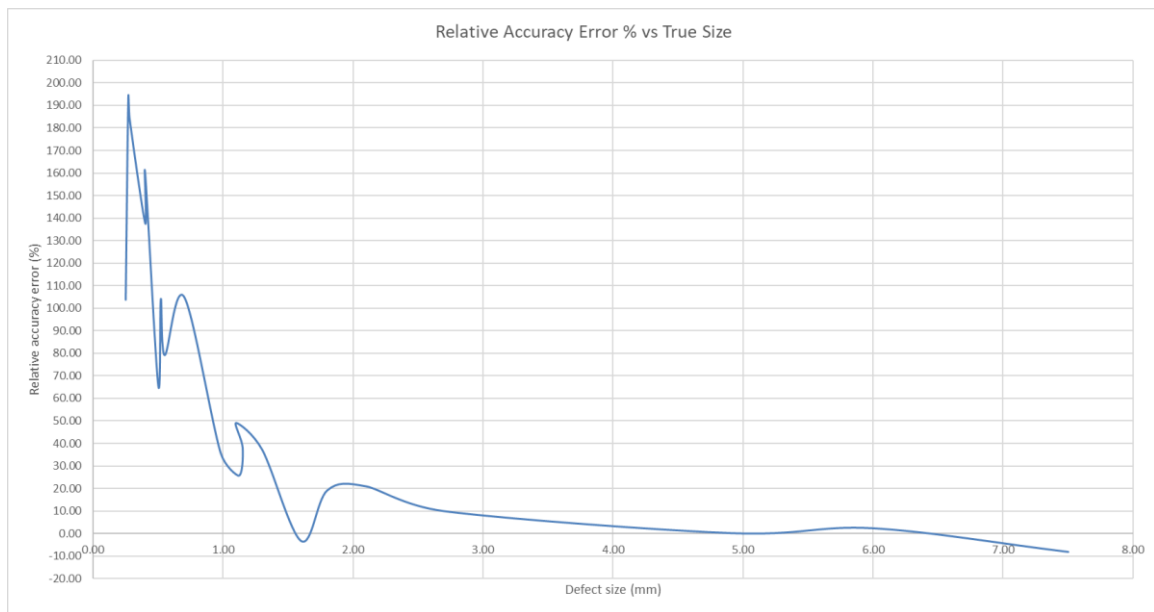
Graph 2 and 3 show the average measurements and a relative accuracy error percentage of the defects compared to the true size (Table 4). As visible on graph 2, the gap between the average measurements and true size decreases as the defect size increases. The error percentage drops significantly (graph 3) decreasing from an error of 190% to 8%. Usually, a 5% Accuracy error rate is accepted, thus in this case showing significant accuracy limitations at smaller defect sizes.

Table 4: Accuracy error percentage

| Defect | true size | RELATIVE ERROR TO TRUE SIZE (%) |        |        |        |        |        |        |        |        |        | AVG    |
|--------|-----------|---------------------------------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|
|        |           | Op1                             | Op2    | Op3    | Op4    | Op5    | Op6    | Op7    | Op8    | Op9    | Op10   |        |
| A      | 0.25      | 300.00                          | 100.00 | 100.00 | 98.00  | 100.00 | 100.00 | 300.00 | 20.00  | 100.00 | 220.00 | 143.80 |
| B      | 0.27      | 270.37                          | 100.00 | 270.37 | 169.26 | 344.44 | 85.19  | 270.37 | 344.44 | 85.19  | 196.30 | 213.59 |
| C      | 0.28      | 257.14                          | 100.00 | 78.57  | 170.71 | 257.14 | 328.57 | 257.14 | 150.00 | 78.57  | 364.29 | 204.21 |
| D      | 0.40      | 200.00                          | 150.00 | 150.00 | 127.50 | 25.00  | 150.00 | 150.00 | 100.00 | 50.00  | 275.00 | 137.75 |
| E      | 0.40      | 250.00                          | 150.00 | 175.00 | 145.00 | 200.00 | 150.00 | 150.00 | 125.00 | 50.00  | 300.00 | 169.50 |
| F      | 0.50      | 120.00                          | 100.00 | 60.00  | 58.00  | 80.00  | 100.00 | 140.00 | 0.00   | 100.00 | 100.00 | 85.80  |
| G      | 0.52      | 73.08                           | 188.46 | 92.31  | 94.62  | 188.46 | 111.54 | 92.31  | 34.62  | 92.31  | 73.08  | 104.08 |
| H      | 0.55      | 9.09                            | 63.64  | 118.18 | 73.64  | 118.18 | 45.45  | 81.82  | 27.27  | 136.36 | 190.91 | 86.45  |
| I      | 0.70      | 185.71                          | 128.57 | 71.43  | 92.86  | 114.29 | 28.57  | 42.86  | 42.86  | 128.57 | 214.29 | 105.00 |
| J      | 0.98      | 93.88                           | 104.08 | 63.27  | 33.47  | 2.04   | 18.37  | 2.04   | 42.86  | 48.98  | 83.67  | 49.27  |
| K      | 1.12      | 10.71                           | 60.71  | 60.71  | 22.50  | 55.36  | 10.71  | 33.93  | 16.07  | 60.71  | 78.57  | 41.00  |
| L      | 1.15      | 91.30                           | 13.04  | 30.43  | 35.22  | 56.52  | 13.04  | 30.43  | 4.35   | 56.52  | 73.91  | 40.48  |
| M      | 1.10      | 81.82                           | 45.45  | 36.36  | 45.45  | 81.82  | 27.27  | 81.82  | 45.45  | 54.55  | 100.00 | 60.00  |
| N      | 1.30      | 69.23                           | 53.85  | 53.85  | 33.08  | 61.54  | 30.77  | 15.38  | 30.77  | 30.77  | 53.85  | 43.31  |
| O      | 1.60      | 25.00                           | 25.00  | 6.25   | 2.50   | 50.00  | 43.75  | 25.00  | 6.25   | 25.00  | 25.00  | 23.38  |
| P      | 1.80      | 33.33                           | 11.11  | 77.78  | 18.89  | 11.11  | 22.22  | 38.89  | 38.89  | 22.22  | 38.89  | 31.33  |
| Q      | 2.10      | 66.67                           | 19.05  | 42.86  | 18.57  | 14.29  | 9.52   | 4.76   | 23.81  | 4.76   | 52.38  | 25.67  |
| R      | 2.70      | 3.70                            | 7.41   | 29.63  | 10.00  | 11.11  | 18.52  | 29.63  | 18.52  | 7.41   | 29.63  | 16.56  |
| S      | 4.90      | 16.33                           | 8.16   | 10.20  | 0.61   | 8.16   | 8.16   | 12.24  | 12.24  | 14.29  | 10.20  | 10.06  |
| T      | 6.00      | 16.67                           | 8.33   | 8.33   | 2.83   | 8.33   | 3.33   | 8.33   | 0.00   | 11.67  | 11.67  | 7.95   |
| U      | 7.50      | 6.67                            | 4.00   | 13.33  | 6.87   | 20.00  | 16.67  | 6.67   | 13.33  | 13.33  | 8.00   | 10.89  |
| AVG    |           | 103.84                          | 68.61  | 73.76  | 59.98  | 86.09  | 62.94  | 84.46  | 52.23  | 55.77  | 119.03 |        |



Graph 2: True Size & Average of measurement comparison



*Graph 3: Accuracy Error Percentage vs True Size*

Regression analysis identifies which predictors in a model have statistical significance and which do not, and determines the extent to which the model explains the overall variability in the data. This analysis was performed for given data set, which resulted in significant results and therefore suggests there is a significant relationship between the defect size and the measurement accuracy.

Table 5: SPSS Regression Analysis Results

| Variables Entered/Removed <sup>a</sup> |                        |                   |        |
|----------------------------------------|------------------------|-------------------|--------|
| Model                                  | Variables Entered      | Variables Removed | Method |
| 1                                      | True size <sup>b</sup> | .                 | Enter  |
| a. Dependent Variable: Median          |                        |                   |        |
| b. All requested variables entered.    |                        |                   |        |

| Model Summary |                   |          |                   |                            |
|---------------|-------------------|----------|-------------------|----------------------------|
| Model         | R                 | R Square | Adjusted R Square | Std. Error of the Estimate |
| 1             | ,995 <sup>a</sup> | ,990     | ,990              | ,17727477762               |

a. Predictors: (Constant), True size

| ANOVA <sup>a</sup> |            |                |    |             |          |                    |
|--------------------|------------|----------------|----|-------------|----------|--------------------|
| Model              |            | Sum of Squares | df | Mean Square | F        | Sig.               |
| 1                  | Regression | 62,097         | 1  | 62,097      | 1975,944 | <,001 <sup>b</sup> |
|                    | Residual   | ,597           | 19 | ,031        |          |                    |
|                    | Total      | 62,694         | 20 |             |          |                    |

a. Dependent Variable: Median

b. Predictors: (Constant), True size

| Coefficients <sup>a</sup> |            |                             |            |                           |        |
|---------------------------|------------|-----------------------------|------------|---------------------------|--------|
| Model                     |            | Unstandardized Coefficients |            | Standardized Coefficients |        |
|                           |            | B                           | Std. Error | Beta                      | t      |
| 1                         | (Constant) | ,544                        | ,052       |                           | 10,552 |
|                           | True size  | ,881                        | ,020       | ,995                      | 44,452 |

a. Dependent Variable: Median

## R<sup>2</sup>

The R<sup>2</sup> value is provided by the regression analysis. This value indicates the strength of the relationship between the independent and dependent variables. A high R<sup>2</sup> indicates a well-fitted model, meaning that the linear regression equation effectively explains the observed variation in accuracy measurements [14]. However, the use of R<sup>2</sup> as a model of quality is criticized as it is sensitive to sample variance and is therefore unable to guarantee a good fit [15].

RQ1: The R<sup>2</sup> provided by the regression analysis was 0,990 (table 5). which suggests that 99% of the variability in the accuracy of the measurements is explained by the variability in defect size. This is a positive, and very high R<sup>2</sup>, which suggests a strong relationship and that the defect size is a good predictor of measurement accuracy.

***t-value***

The t-value is another way of indicating whether the coefficient associated with the predictor variable (independent variable) is statistically significant since it measures how many standard errors the estimated coefficient is away from zero. The given t-values for the regression analysis by RQ1 are considerably high, which indicates a significant relationship, since it suggests greater evidence against the null hypothesis.

***Hypothesis testing:***

Hypothesis tests are performed on the coefficients to assess the statistical significance of a certain relationship, in this research the defect size and measurement accuracy. The least squares method is often used for developing estimates of the model parameters.

A null hypothesis and alternative hypothesis should be conducted to investigate the relationship. The null Hypothesis ( $H_0$ ) (stated by the author) states that there is no significant relationship between defect size and measurement accuracy, while the alternative hypothesis ( $H_1$ ) proves otherwise. This is assessed by the slope of the regression model.

$H_0: \beta_1 = 0$

$H_1: \beta_1 \neq 0$  (Significant relationship between defect size and measurement accuracy)

The null hypothesis must be rejected in favor of the alternative hypothesis, by testing the  $H_0$ . This can be done in various ways, namely the p-value, confidence interval, and the sampling distribution, which will be discussed in the previous parts.

#### 4.4.2 Regression Analysis 2

Research Question 2: How does the accuracy of the separate technicians compare to the true size?

The regression model which indicates the relationship between the measurement accuracy of each operator to the true value could be explained, by also incorporating equipment and the procedure as following:

$$Y_i = \beta_0 + \beta_1 * X_{Op1} + \beta_2 * X_{Op2} + \beta_3 * X_{Op3} + \dots + \epsilon_i$$

Where:

*$Y_i$  is the defect measurement.*

An Analysis of Variance test (ANOVA) was executed using SPSS, to conclude this research question. If data on different used equipment or procedure were given, a possible regression model could have been:

$$Y_i = \beta_0 + \beta_1 * X_{Technician} + \beta_2 * X_{Equipment} + \beta_3 * X_{Procedure} + \epsilon_i$$

Where:

*$Y_i$  is the defect measurement.*

However, only data points of each operator were given.

#### 4.4.3 Hypothesis Testing

In the same way as for RQ1, a hypothesis test was performed for RQ2.

H0: There is no significant difference in the mean of measurements between operators

H1: At least one operator's mean measurement is different from the others

#### 4.4.4 ANOVA Analysis and Goodness of Fit

An ANOVA test is possible when there are over 21 observations per group. With 21 defect sizes, this test was possible [16]. It is a statistical method used to test the hypothesis for a comparison of means between groups, in this case the operators [17].

##### ***P-value***

The p-value is equal to the probability of a value at least as large as the deviation from the average. If the p-value is below the chosen significance level ( $p < 0.05$ ) the null hypothesis can be rejected and the model is statistically significant [17], [18].

The p-value provided by the ANOVA test analysis, was significant for each operator ( $p < 0.001$ ), indicating the stated H0 could be rejected. Thus, proving a significant difference between the means of operators.

##### ***F-statistic***

The ANOVA test provides the F statistic, which in the context of linear regression assesses the overall significance of the regression model when assessing the sizing accuracy of the individual technicians, equipment, and procedure. The F-statistic is a ratio of two variances of the variance explained by the model to the variance not explained by the model. A high F-statistic suggests that there are significant differences in measurement accuracy among the different measurements by each operator [17], [18].

The given F statistic for each operator was considered to be high, which means that neither operator's measurements are consistent in accuracy across all defect sizes, and have significant variations in accuracy across different defect sizes.

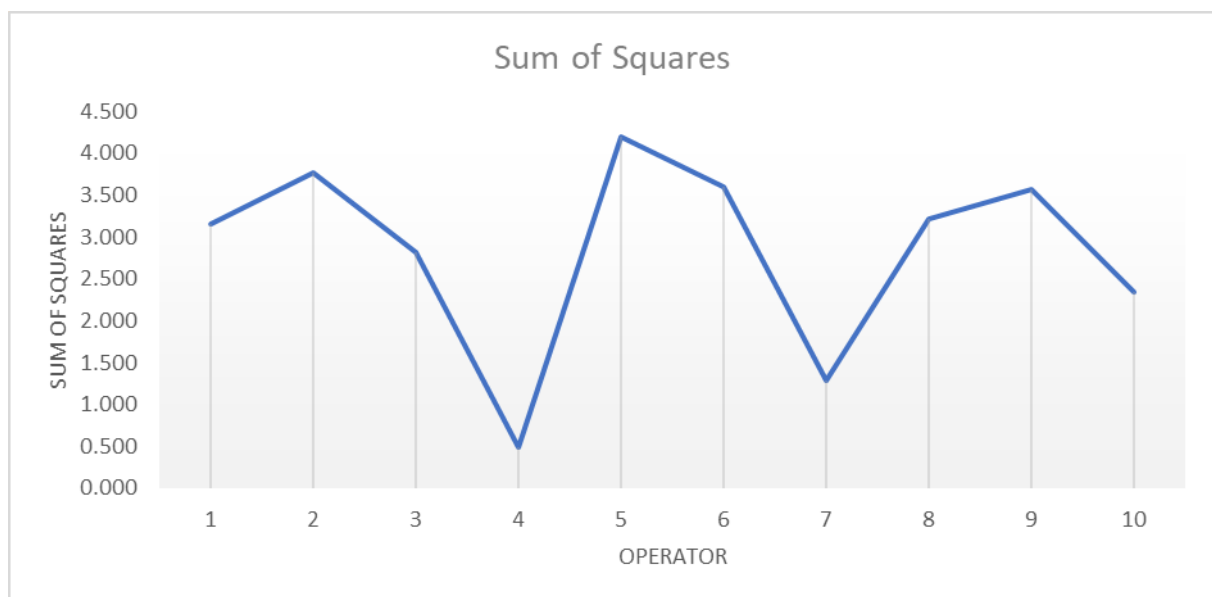
##### ***Residual***

Linear regression makes assumptions about the distribution of errors (residuals). A higher residual means that the model's prediction for a specific observation is further from the actual observed value, therefore a larger prediction error. The residual is needed to compute the standard error of the estimate (SEE) [19], [20].

## ***Sum of squares***

The sum of squares can provide insights into how well the true value predicts each Op measurement. A good fit would be indicated by a high proportion of explained variability (SSR) to the total variability (SST), low SSE, and significant F-statistic. These collectively help assess the accuracy and effectiveness of the regression model in explaining the observed measurements.

A higher Sum of squares indicates that operator contributes to a greater variability or dispersion, showing operator Four and Seven as the most accurate (Graph 4) [20], [21].



*Graph 4: Sum of Squares, operator comparison*

### ***Residual sum of squares***

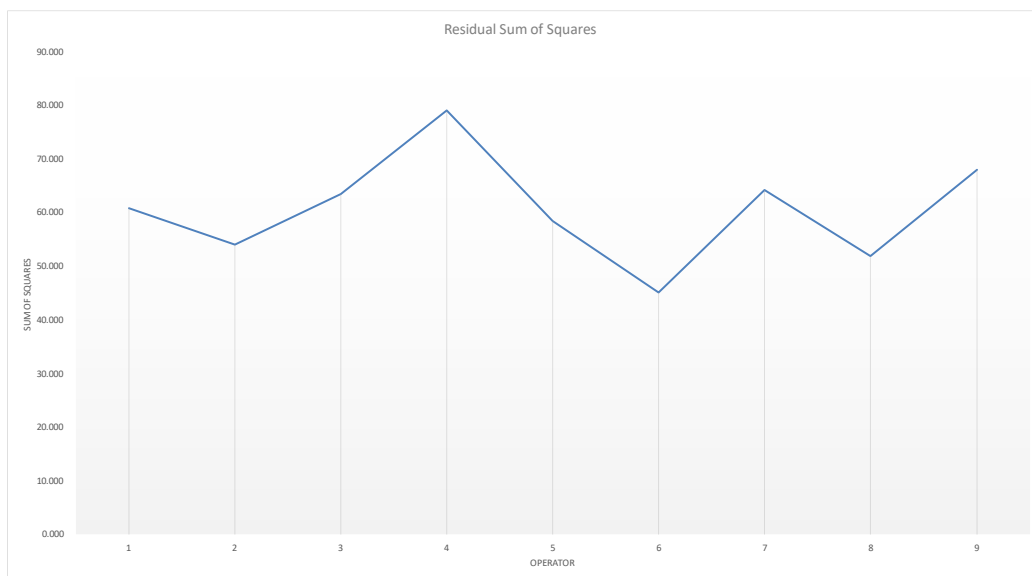
The SSE measures the overall deviation of each measurement from the predicted values. And reflects the measurement errors made by the operators that are not explained by the true values.

$$SSE = \sum_{i=1}^N (Y_i - \hat{Y}_i)^2$$

The sum of squares of the regression quantifies the proportion of the total variability in the dependent variable, measurement accuracy by each operator, that is explained by the regression model.

$$SSR = \sum_{i=1}^N (\hat{Y}_i - \bar{Y})^2$$

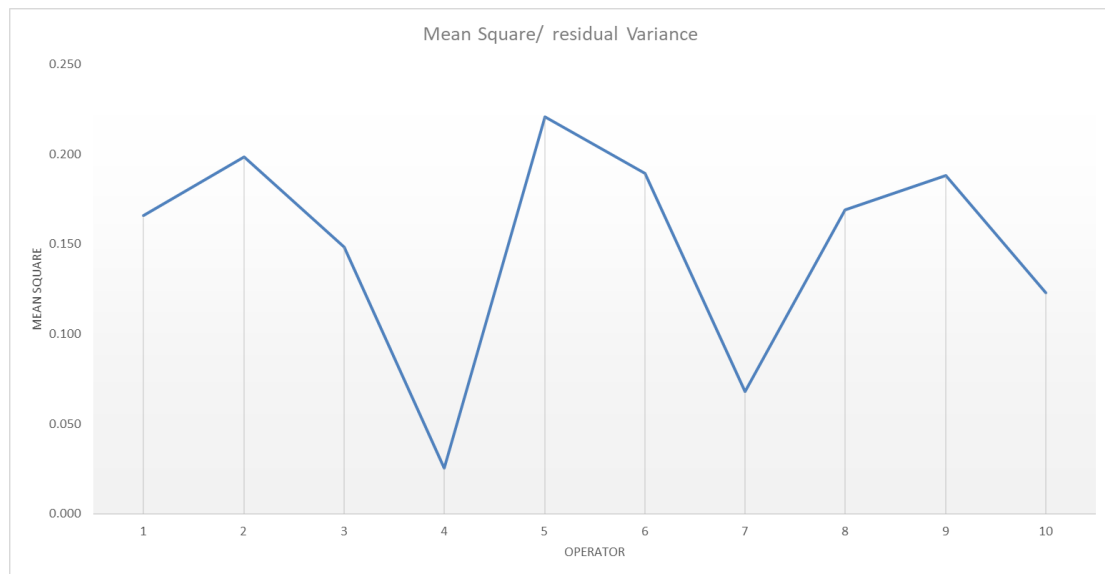
A higher SSR and lower SSE indicate a better-fit model with more explained variability and less unexplained variability. Graph 5 shows the Residual sum of squares, again indicating 4 and 7 with more explained variability.



*Graph 5: Residual Sum of Squares*

### ***Mean square or residual variance***

The mean square indicates the variance/variability of the measurements. The operators indicated with a higher residual variance are less accurate, as larger variability or errors can affect the reliability of predictions. Graph 6 shows operator 5 and 9 as the least accurate.

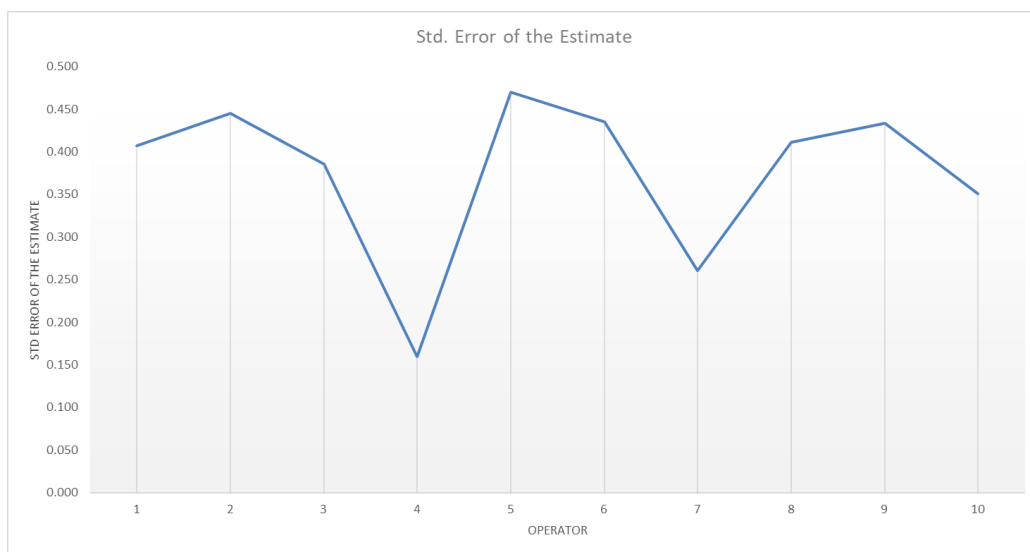


*Graph 6: Mean Square/ Residual Variance*

### ***Standard error of the estimate (SEE)***

Linear regression analysis provides the SEE is the standard deviation of the residuals. It quantifies the average magnitude of the differences between the observed and predicted Y values. It provides information about how well the model's predictions match the actual observed true value by quantifying the dispersion of the residuals [20], [22].

The standard error of the estimate is calculated based on the sampling distribution, which was explained before. The operators with a lower SEE are considered a better-fitted model, due to their lower variability (Graph 7).



*Graph 7: Standard Error of the Estimate*

## **PAIRED SAMPLE T-TEST**

RQ2:

### ***t-value***

The t-value is another way of indicating whether the coefficient associated with the predictor variable (independent variable) is statistically significant, since it measures how many standard errors the estimated coefficient is away from zero [17], [23].

The given t-values for the regression analysis by RQ1 are considerably high, which indicates a significant relationship between defect size and measurement accuracy.

The paired sample t-test was performed by pairing each operator with the true size. The results provided the average differences between the operator's measurements and the true sizes, which indicates their accuracy. A t-value closer to zero suggests that the operator has been, on average, accurate in their measurement [23].

### ***Confidence interval (CI)***

The confidence interval provided by the paired sample t-test indicates a range that is likely to include the actual mean difference between the paired observations. E.g; the 95% CI runs from 0.518 to 0.880, which suggests that the true mean difference is likely between those values. If the CI does not include zero, it means the null hypothesis could be rejected and the results are significant [24]. The confidence interval is connected to the central limit theorem, which requires approximately 30 samples to run a paired sample t-test [25].

Each operator performed 21 measurements and was paired with the true size for the paired sample t-test, which resulted in 21 pairs for each operator. This is a limited sample size to conduct a proper analysis of the confidence interval and resulted in insignificant results for operators 5, 6, 8, and 9. These insignificant results could not be clarified, since other statistical analyses proved a significant relationship. The margin error of the CI could be a possible explanation [26].

- Narrow Interval: Indicates a more precise estimate of the mean difference.
- Wide Interval: Suggests more uncertainty in the estimate.
- Doesn't include Zero: Reinforces the significance of the mean difference.

Table 6: paired samples test -CI results.

| Paired Samples Correlations |                  |    |             |              |             |
|-----------------------------|------------------|----|-------------|--------------|-------------|
|                             |                  | N  | Correlation | Significance |             |
|                             |                  |    |             | One-Sided p  | Two-Sided p |
| Pair 1                      | Op1 & true size  | 21 | ,981        | <,001        | <,001       |
| Pair 2                      | Op2 & true size  | 21 | ,973        | <,001        | <,001       |
| Pair 3                      | Op3 & true size  | 21 | ,974        | <,001        | <,001       |
| Pair 4                      | Op4 & true size  | 21 | ,996        | <,001        | <,001       |
| Pair 5                      | Op5 & true size  | 21 | ,956        | <,001        | <,001       |
| Pair 6                      | Op6 & true size  | 21 | ,971        | <,001        | <,001       |
| Pair 7                      | Op7 & true size  | 21 | ,992        | <,001        | <,001       |
| Pair 8                      | Op8 & true size  | 21 | ,976        | <,001        | <,001       |
| Pair 9                      | Op9 & true size  | 21 | ,969        | <,001        | <,001       |
| Pair 10                     | Op10 & true size | 21 | ,981        | <,001        | <,001       |

| Paired Samples Test |                  |                    |                |                 |                                           |              |       |    |             |             |
|---------------------|------------------|--------------------|----------------|-----------------|-------------------------------------------|--------------|-------|----|-------------|-------------|
|                     |                  | Paired Differences |                |                 |                                           | Significance |       |    |             |             |
|                     |                  | Mean               | Std. Deviation | Std. Error Mean | 95% Confidence Interval of the Difference |              | t     | df | One-Sided p | Two-Sided p |
|                     |                  |                    |                |                 | Lower                                     | Upper        |       |    |             |             |
| Pair 1              | Op1 - true size  | ,69904761905       | ,39698746532   | ,08662976713    | ,51834109137                              | ,87975414673 | 8,069 | 20 | <,001       | <,001       |
| Pair 2              | Op2 - true size  | ,30857142857       | ,46056797234   | ,10050417123    | ,09892340108                              | ,51821945606 | 3,070 | 20 | ,003        | ,006        |
| Pair 3              | Op3 - true size  | ,38952380952       | ,54035614358   | ,11791537763    | ,14355664192                              | ,63549097713 | 3,303 | 20 | ,002        | ,004        |
| Pair 4              | Op4 - true size  | ,31461904762       | ,25836959500   | ,05638086792    | ,19701061801                              | ,43222747723 | 5,580 | 20 | <,001       | <,001       |
| Pair 5              | Op5 - true size  | ,20857142857       | ,67610861342   | ,14753899519    | -,0991895224                              | ,51633237959 | 1,414 | 20 | ,086        | ,173        |
| Pair 6              | Op6 - true size  | ,07285714286       | ,51385934707   | ,11213330260    | -,1610488276                              | ,30676311329 | ,650  | 20 | ,262        | ,523        |
| Pair 7              | Op7 - true size  | ,50380952381       | ,25433199151   | ,05549979061    | ,38803898927                              | ,61958005835 | 9,078 | 20 | <,001       | <,001       |
| Pair 8              | Op8 - true size  | ,14190476190       | ,45591248116   | ,09948825977    | -,0656241114                              | ,34943363522 | 1,426 | 20 | ,085        | ,169        |
| Pair 9              | Op9 - true size  | ,01333333333       | ,55128335122   | ,12029988983    | -,2376078396                              | ,26427450622 | ,111  | 20 | ,456        | ,913        |
| Pair 10             | Op10 - true size | ,75142857143       | ,42617233268   | ,09299842731    | ,55743725140                              | ,94541989146 | 8,080 | 20 | <,001       | <,001       |

## Operator Relative Accuracy Error Analysis

Since the analysis of the previous statistical values show the same trend in proving accuracy of each operator, The operators have been sorted by their accuracy, using the Mean Square value. Table 8 shows this sorted list, with operator Four being the most accurate, and operator 5 being the least accurate throughout their measurements. The difference in accuracy between them is displayed in percentage for ease of analysis. Showing a 158% difference in between most and least accurate operator (Table 7).

The accuracy of the operators is hard to analyse as all of them have quite a high average percentage error throughout the range, probably implying inaccurate equipment or methods. There is still a strong difference between accuracy of operators, showing that improvement in operation methods can be done and this needs to be evaluated. In order to optimise the process

Table 7: Relative Accuracy Error percentage

| RELATIVE ERROR TO TRUE SIZE (%) |           |        |        |        |        |        |        |        |        |        |        |        |
|---------------------------------|-----------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|
| Defect                          | true size | Op1    | Op2    | Op3    | Op4    | Op5    | Op6    | Op7    | Op8    | Op9    | Op10   | AVG    |
| A                               | 0.25      | 300.00 | 100.00 | 100.00 | 98.00  | 100.00 | 100.00 | 300.00 | 20.00  | 100.00 | 220.00 | 143.80 |
| B                               | 0.27      | 270.37 | 100.00 | 270.37 | 169.26 | 344.44 | 85.19  | 270.37 | 344.44 | 85.19  | 196.30 | 213.59 |
| C                               | 0.28      | 257.14 | 100.00 | 78.57  | 170.71 | 257.14 | 328.57 | 257.14 | 150.00 | 78.57  | 364.29 | 204.21 |
| D                               | 0.40      | 200.00 | 150.00 | 150.00 | 127.50 | 25.00  | 150.00 | 150.00 | 100.00 | 50.00  | 275.00 | 137.75 |
| E                               | 0.40      | 250.00 | 150.00 | 175.00 | 145.00 | 200.00 | 150.00 | 150.00 | 125.00 | 50.00  | 300.00 | 169.50 |
| F                               | 0.50      | 120.00 | 100.00 | 60.00  | 58.00  | 80.00  | 100.00 | 140.00 | 0.00   | 100.00 | 100.00 | 85.80  |
| G                               | 0.52      | 73.08  | 188.46 | 92.31  | 94.62  | 188.46 | 111.54 | 92.31  | 34.62  | 92.31  | 73.08  | 104.08 |
| H                               | 0.55      | 9.09   | 63.64  | 118.18 | 73.64  | 118.18 | 45.45  | 81.82  | 27.27  | 136.36 | 190.91 | 86.45  |
| I                               | 0.70      | 185.71 | 128.57 | 71.43  | 92.86  | 114.29 | 28.57  | 42.86  | 42.86  | 128.57 | 214.29 | 105.00 |
| J                               | 0.98      | 93.88  | 104.08 | 63.27  | 33.47  | 2.04   | 18.37  | 2.04   | 42.86  | 48.98  | 83.67  | 49.27  |
| K                               | 1.12      | 10.71  | 60.71  | 60.71  | 22.50  | 55.36  | 10.71  | 33.93  | 16.07  | 60.71  | 78.57  | 41.00  |
| L                               | 1.15      | 91.30  | 13.04  | 30.43  | 35.22  | 56.52  | 13.04  | 30.43  | 4.35   | 56.52  | 73.91  | 40.48  |
| M                               | 1.10      | 81.82  | 45.45  | 36.36  | 45.45  | 81.82  | 27.27  | 81.82  | 45.45  | 54.55  | 100.00 | 60.00  |
| N                               | 1.30      | 69.23  | 53.85  | 53.85  | 33.08  | 61.54  | 30.77  | 15.38  | 30.77  | 30.77  | 53.85  | 43.31  |
| O                               | 1.60      | 25.00  | 25.00  | 6.25   | 2.50   | 50.00  | 43.75  | 25.00  | 6.25   | 25.00  | 25.00  | 23.38  |
| P                               | 1.80      | 33.33  | 11.11  | 77.78  | 18.89  | 11.11  | 22.22  | 38.89  | 38.89  | 22.22  | 38.89  | 31.33  |
| Q                               | 2.10      | 66.67  | 19.05  | 42.86  | 18.57  | 14.29  | 9.52   | 4.76   | 23.81  | 4.76   | 52.38  | 25.67  |
| R                               | 2.70      | 3.70   | 7.41   | 29.63  | 10.00  | 11.11  | 18.52  | 29.63  | 18.52  | 7.41   | 29.63  | 16.56  |
| S                               | 4.90      | 16.33  | 8.16   | 10.20  | 0.61   | 8.16   | 8.16   | 12.24  | 12.24  | 14.29  | 10.20  | 10.06  |
| T                               | 6.00      | 16.67  | 8.33   | 8.33   | 2.83   | 8.33   | 3.33   | 8.33   | 0.00   | 11.67  | 11.67  | 7.95   |
| U                               | 7.50      | 6.67   | 4.00   | 13.33  | 6.87   | 20.00  | 16.67  | 6.67   | 13.33  | 13.33  | 8.00   | 10.89  |
| AVG                             |           | 103.84 | 68.61  | 73.76  | 59.98  | 86.09  | 62.94  | 84.46  | 52.23  | 55.77  | 119.03 |        |

Table 8: Sorted list of operator accuracy

| Operator | Mean Square | % to prev | % to first |
|----------|-------------|-----------|------------|
| op4      | 0.025       |           |            |
| op7      | 0.068       | 90.907    | 90.907     |
| op10     | 0.123       | 57.654    | 131.350    |
| op3      | 0.148       | 18.650    | 141.344    |
| Op1      | 0.166       | 11.174    | 146.725    |
| op8      | 0.169       | 1.819     | 147.559    |
| op9      | 0.188       | 10.672    | 152.237    |
| op6      | 0.189       | 0.737     | 152.547    |
| op2      | 0.198       | 4.621     | 154.446    |
| op5      | 0.221       | 10.797    | 158.629    |

## 5 Conclusion

In the first part of this technical paper, the attenuation coefficient of Two samples has been determined of measurements made with a digital ultrasonic flaw detector. Measurement accuracy could have been increased if the possibility was there to determine the amplitude of the pulses accurately. The measurement precision and calculation of the coefficients was deemed acceptable and successful. In the second part, through various statistical methods and linear regression, based on a through wall size measurements data set, the sizing accuracy of 10 operators and the equipment, procedure was analysed.

Two research questions were formed to answer if defect size is related to the accuracy of the measurements, and if there was a significant difference in accuracy between the operators.

The methods used to analysed showed a significant relationship between defect size and measurement accuracy, ranging from 193% to -8% Accuracy between the smallest and largest defect respectively. Giving reason to assume the equipment is not accurate enough to use at smaller defect sizes.

The high variance in accuracy between operators (table 7) shows a significant difference in operation method to cause this accuracy difference. Which indicates the method and operation can be improved.

The analytical methods consistently deemed significant, although the sample size of the measurements was very small to the habit of statistics, with a too small sample size for a completely accurate CI analysis. The variance in accuracy between operators was consistently proven, with operator Four being the most accurate, and operator Five being the least accurate.

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