# UT data analysis steps for development of automated detection technique of bonding defects in multi-layered structures

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**Abstract:** Multi-layered structures of adhesively bonded similar and dissimilar materials have a high interest in aerospace and automotive industries. Adhesive joining is more advanced technology which allows to join different types of materials, provide uniform load distribution and resistance to corrosion. Adhesive joining and composite materials are the key technology and materials which provide lightening of the structure as well as reduce CO2 emission. Adhesively bonded similar and dissimilar materials are usually used in secondary load carriers due to their advanced mechanical characteristics. However, this structures are still limited in use due to the absence of reliable method suitable for investigation of multi-layered structures and, especially, dissimilar material joints. It is problematic to detect bonding defects in multi-layered structures without complex modelling of sound propagation performed by numerical methods. This factor limits practical application of the technique.

Ultrasonic testing (UT) is the widely used non-destructive method for inspection of different materials and structures. A lot of research has been carried out to evaluate adhesion quality using ultrasonic inspection. This technique is one of the most suitable techniques for investigation of multi-layered structures. However, complex modelling of wave propagation is almost always required for the detection of bonding defects due to uncertainty factors such as inspection execution, component geometry, surface preparation, thickness of adhesive and adherents and signal reverberation which influence on the detection of interface defects. Therefore, the complex modelling and numerical evaluations can be eliminated by developing a robust method for automatic analysis of ultrasonic NDT data for detection of bonding defects in multi-layered structures. As a result, the objective of this work is to create steps of analysis of UT data for development of automated defect detection technique.

The experimental investigation of adhesively bonded materials was performed using ultrasonic inspection. The collected data was analyzed. Influential factors which have an impact on the interface defect detection were determined. The valuable features which are capable to increase probability of interface defect detection and features related to the defects for development of data post-processing technique were determined and extracted. The basic steps of analysis and algorithm of automated detection of interface defects are provided in this work. The reliability of the technique was evaluated and detected defects were sized.

Key words: data post-processing, automatic analysis, ultrasonic, adhesive joints, interface defects

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# UT Data Analysis Steps For Development of Automated Detection Technique of Bonding Defects in Multi-layered Structures


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# Relevance

- Development trends and main demands in automotive and aerospace industry is reduction of fuel consumption and carbon dioxide emission. In addition, adhesive bonding technique lightens the weight of entire structure.
- Multilayered structures bonded adhesively has improved performance:

  - Even distribution of mechanical strength;

  - Superior characteristics of fatigue life, impact resistance and residual strength.

- Reliable method for detection of defects in such structures should be developed to ensure life, health and environmental safety.

# Problem

- Requirement of complex modeling of wave propagation for the detection of bonding defects;
- Related to samples:

- multilayered structure
- complex geometry
- quite different elastic and acoustic properties of dissimilar materials
- thin thickness of components
- surface preparation.

# Objective & Tasks

- The objective of this work is to create steps of analysis of UT data for development of automated defect detection technique.

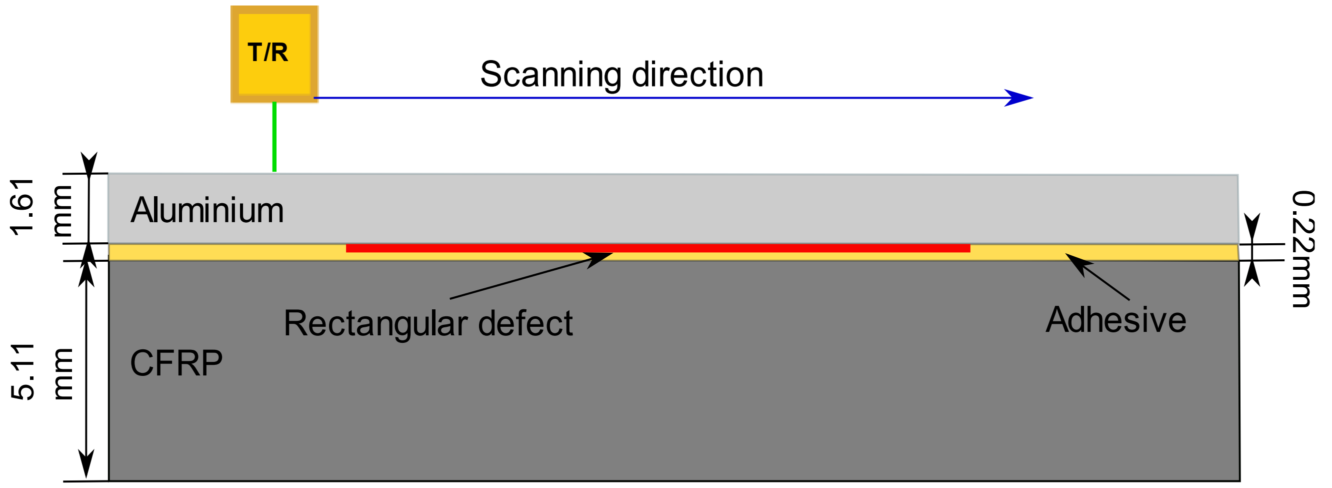
- Tasks:

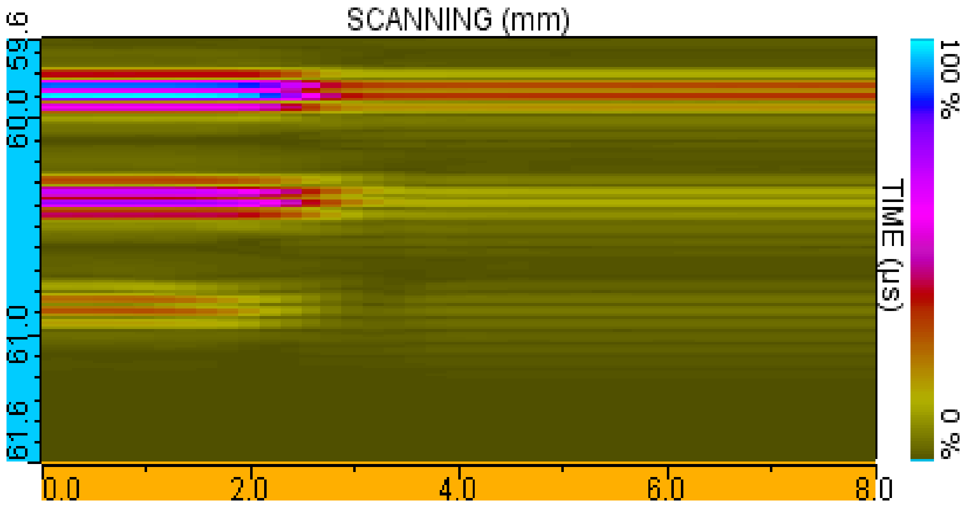
1. Development of the technique to eliminate influential factors affecting probability of bonding defects detection
2. Determination & extraction of UT features capable to increase probability of defect detection
3. Evaluation of extracted features performance using -6dB threshold sizing method

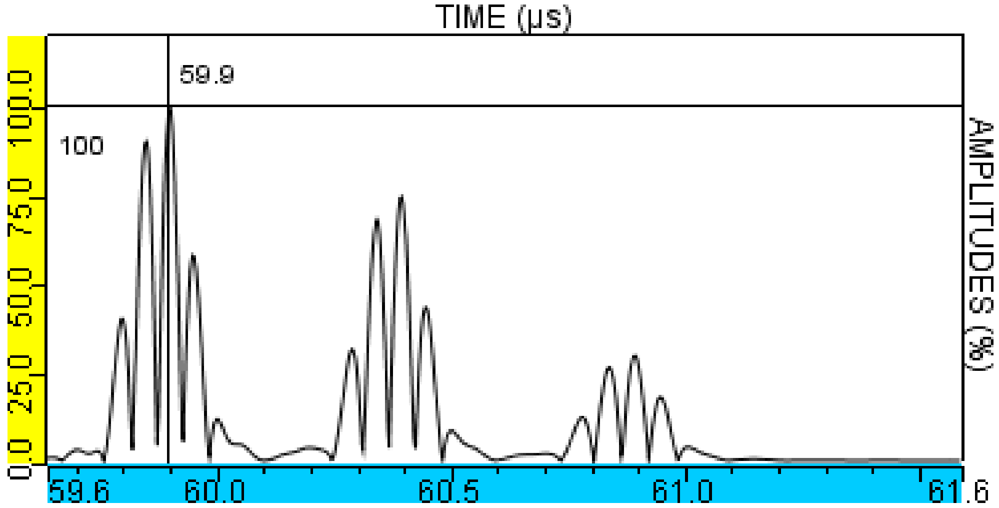
# Task 1: Development of the technique to eliminate influential factors affecting probability of bonding defects detection

# Determination of Influential Factors: Sensitivity Analysis

- Calibration



# Determination of Influential Factors: Sensitivity Analysis

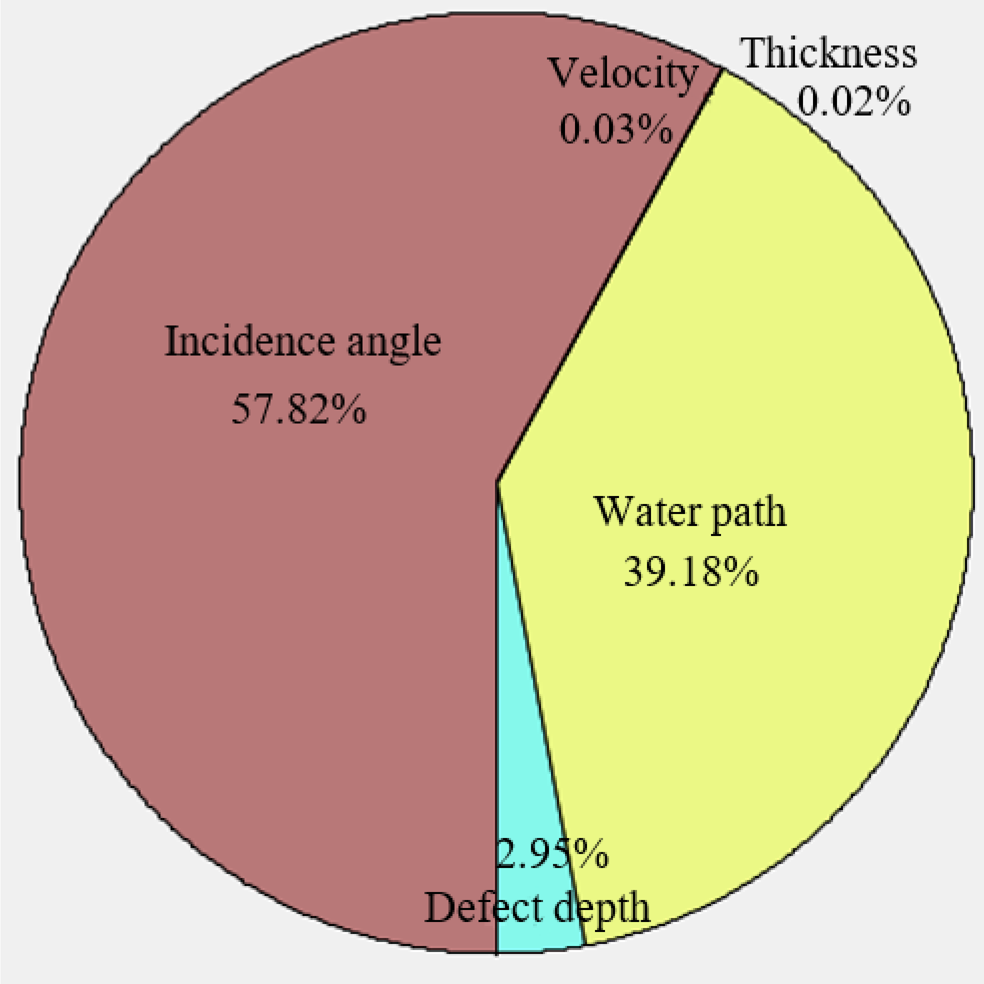
- Metamodel computation

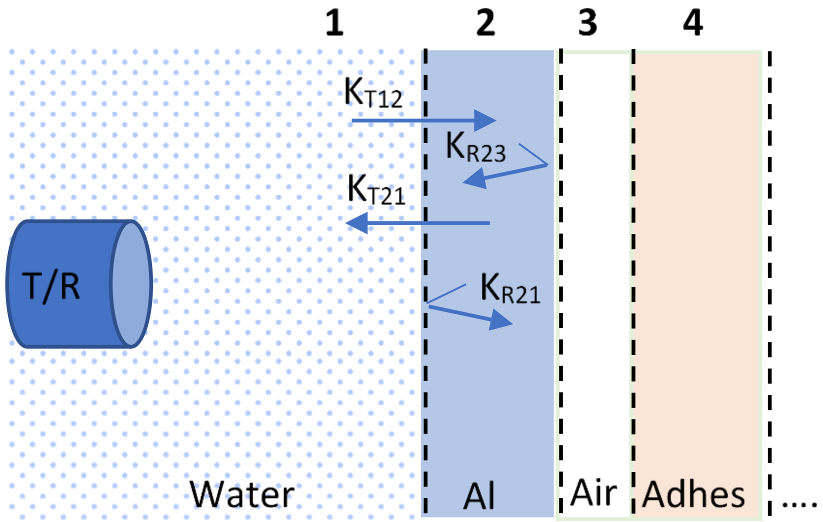
| Parameters | Mean value | Variation range | Statistical distribution law |
|---|---|---|---|
| Longitudinal velocity of ultrasound in aluminium | 6 363 m/s | [6 313 m/s; 6 500 m/s] | Normal |
| Defect length along x axis | 2.625 mm | [0.25 mm; 5 mm] | Constant/ Char. value |
| Defect depth position in adhesive | 1.72 mm | [1.61 mm; 1.82 mm] | Uniform |
| Distance between sample surface and transdcuer | 44.03 mm | [43.5 mm; 44.03 mm] | Uniform |
| Thickness of aluminium | 1.61 mm | [1.60 mm; 1.61 mm] | Normal |
| Incidence angle | 0° | [-6°; 0°] | Uniform |

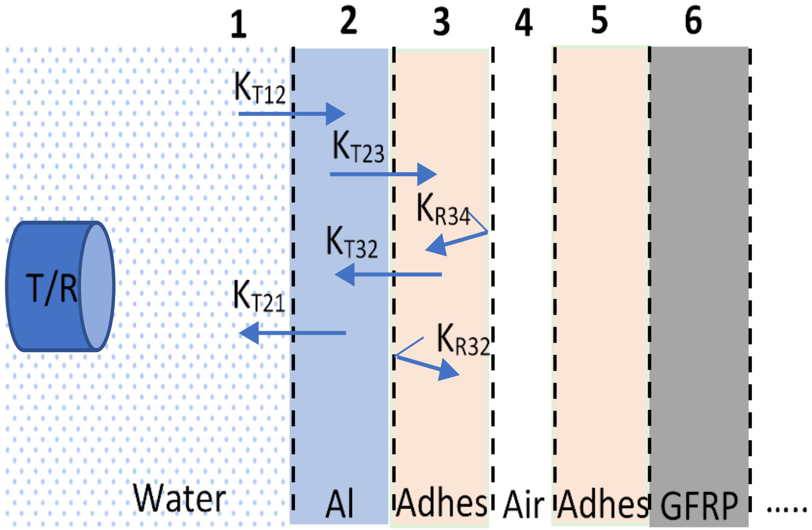
# Determination of Influential Factors: Sensitivity Analysis

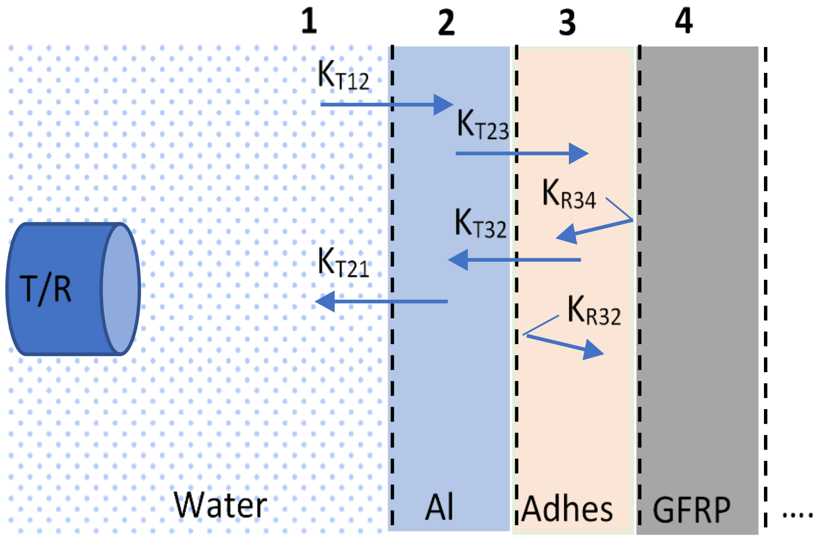
- Metamodel computation

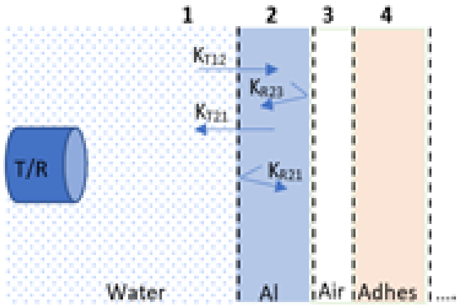
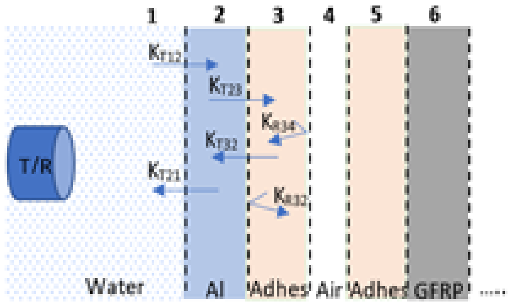
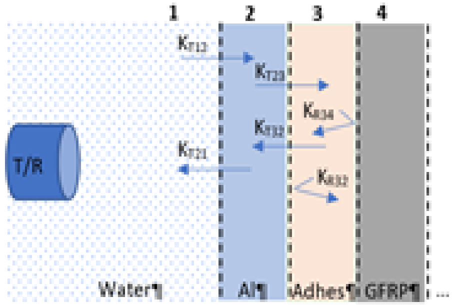
| Uncertain parameters | Sensitivity, indices of Sobol | Proportion value, % |
|---|---|---|
| Longitudinal wave velocity | 0.04 | 0.03 |
| Defect depth | 3.53 | 2.95 |
| Water path (distance between transducer and surface) | 46.90 | 39.18 |
| Thickness of aluminium | 0.03 | 0.02 |
| Incidence angle | 69.21 | 57.82 |





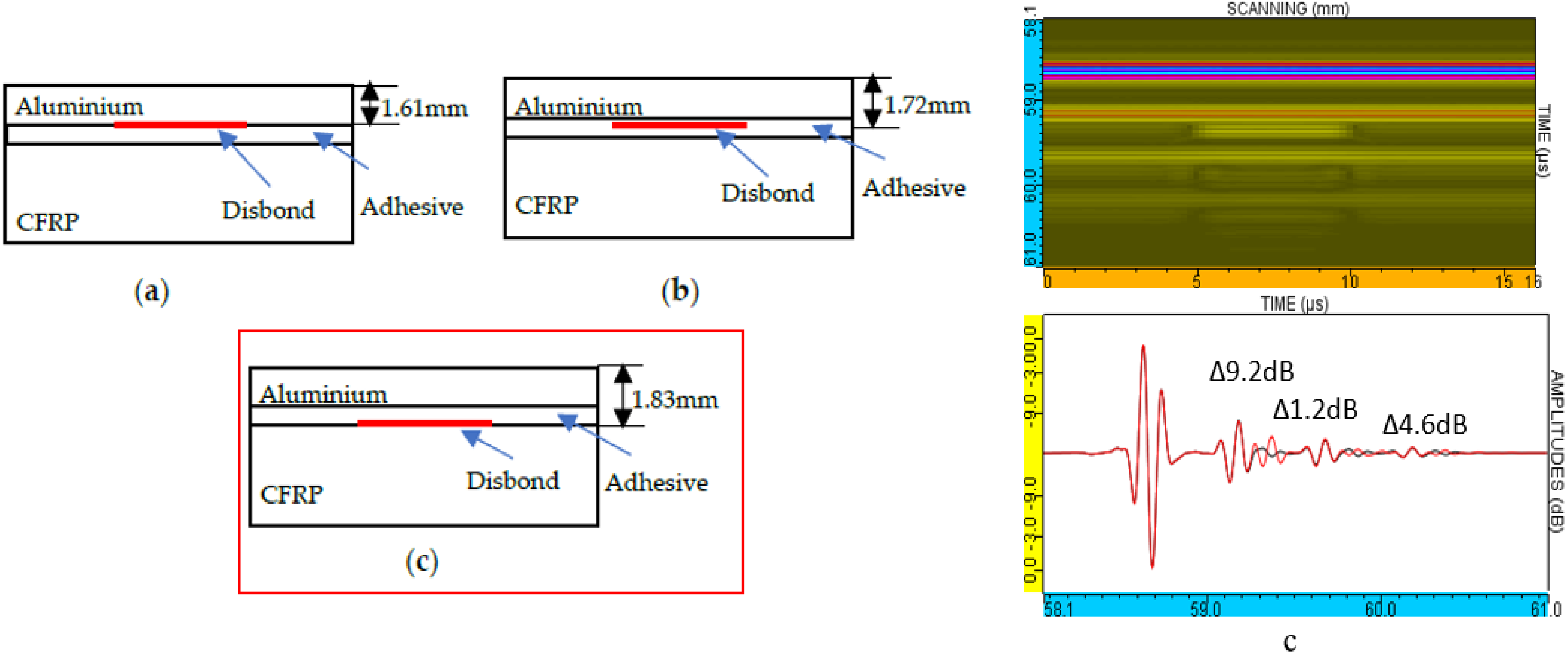



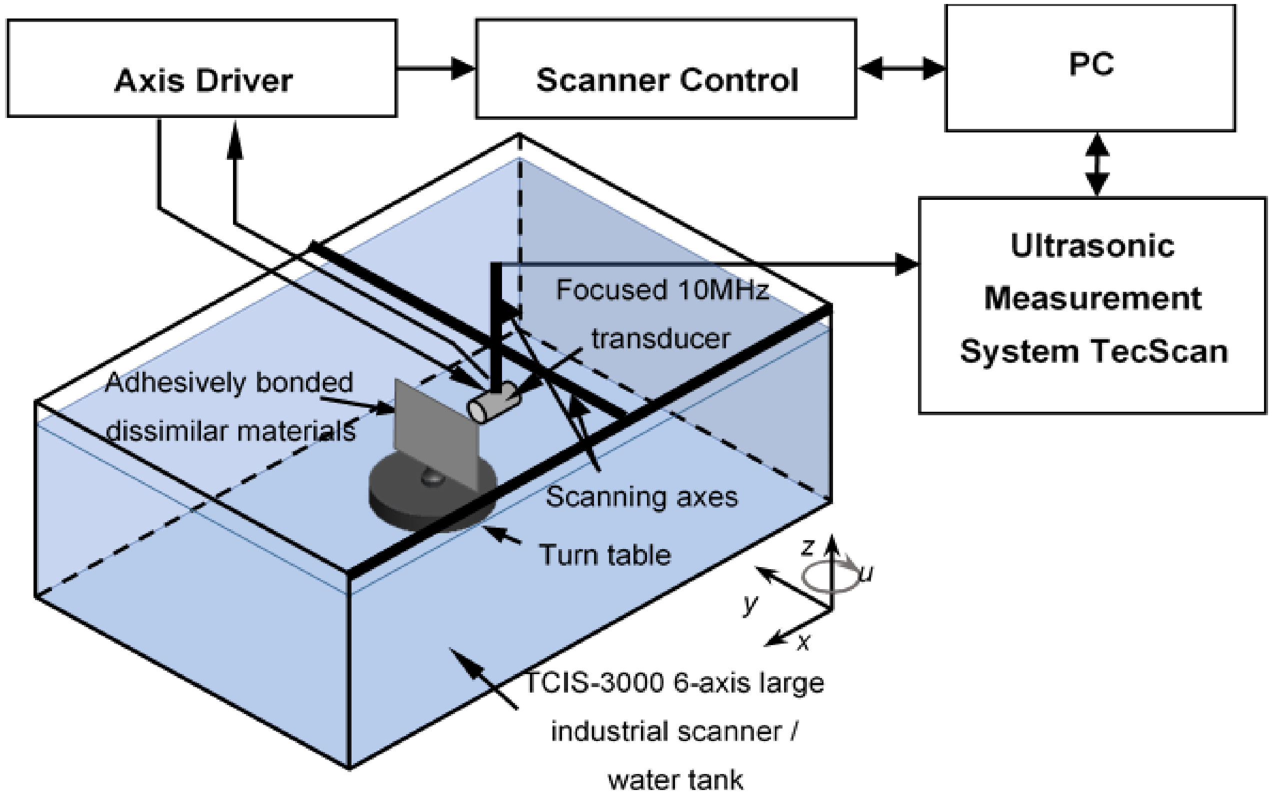

| Amplitude of multiple reflections | Aluminium-disbond  | Adhesive-disbond  | Adhesive-GFRP  |
|---|---|---|---|
| $A_1$ | −0.2915 | −0.1451 | 0.0468 |
| $A_2$ | −0.2424 | 0.1020 | 0.0106 |
| $A_3$ | −0.2016 | −0.0717 | 0.0024 |
| $A_4$ | −0.1676 | −0.0504 | 0.00054 |

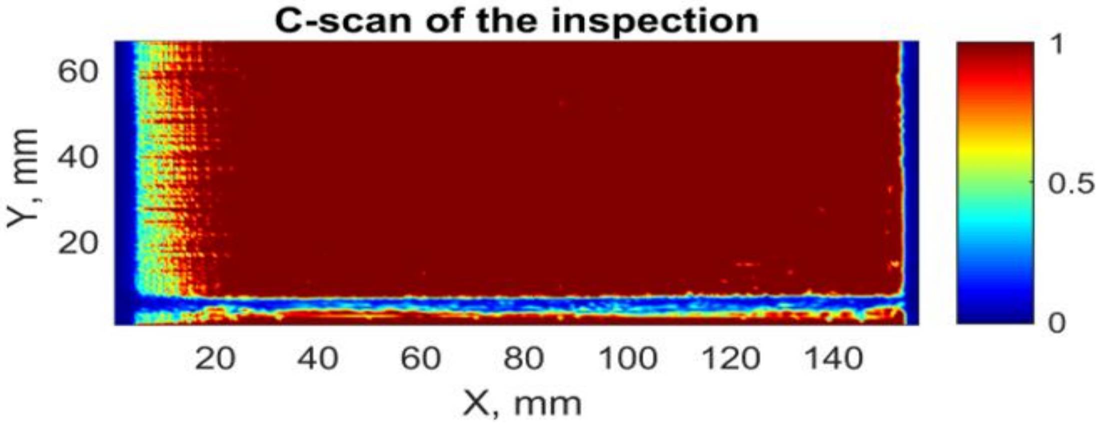
# Numerical Evaluations

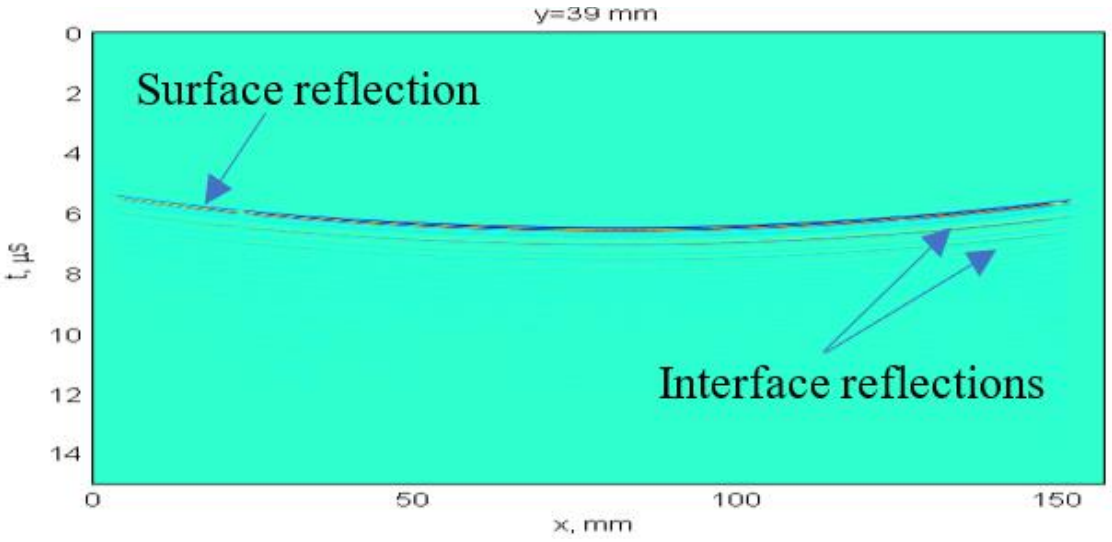
## Inspection performed from the metal side of the sample



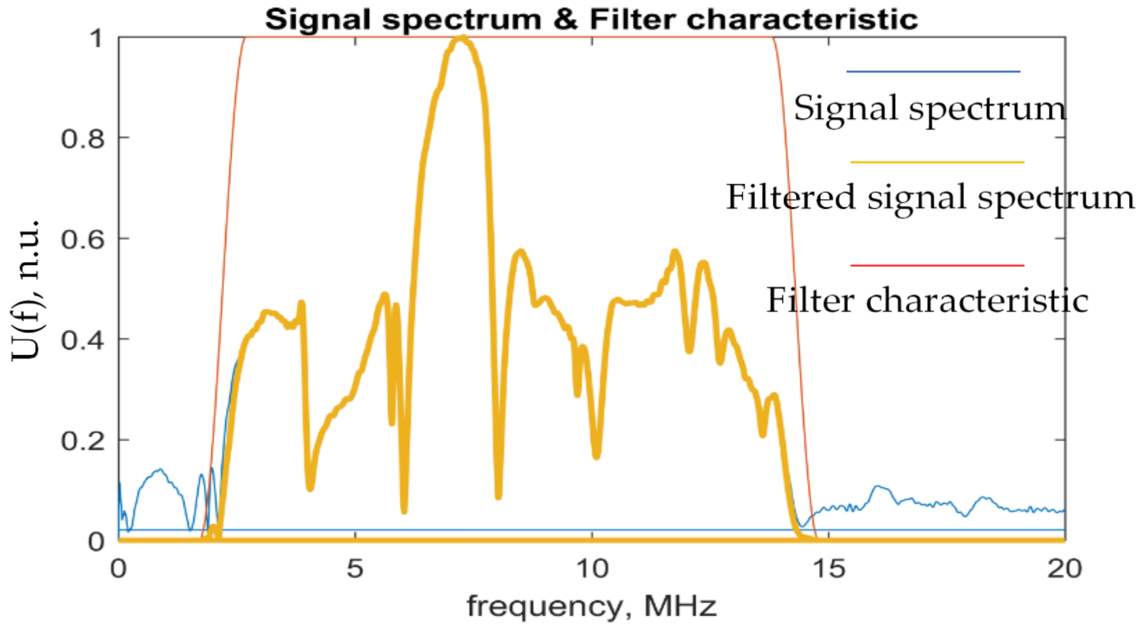
# Experimental Investigation



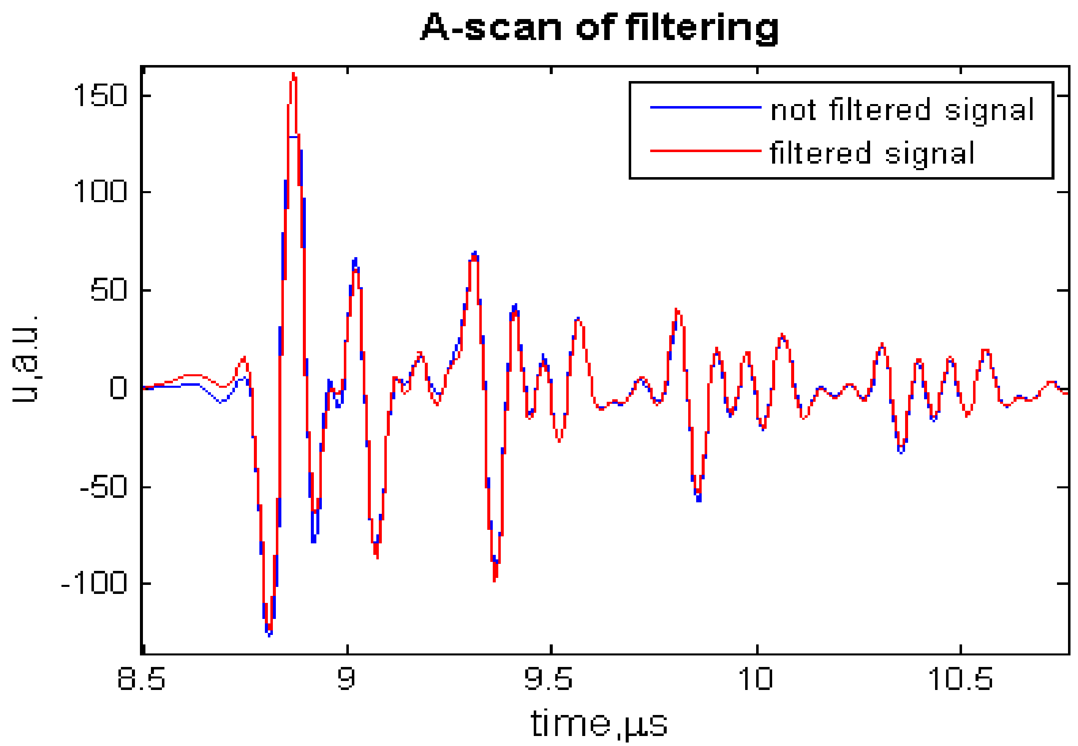
# Development of Post-processing Algorithm: Signal Filtering & Time Alignment



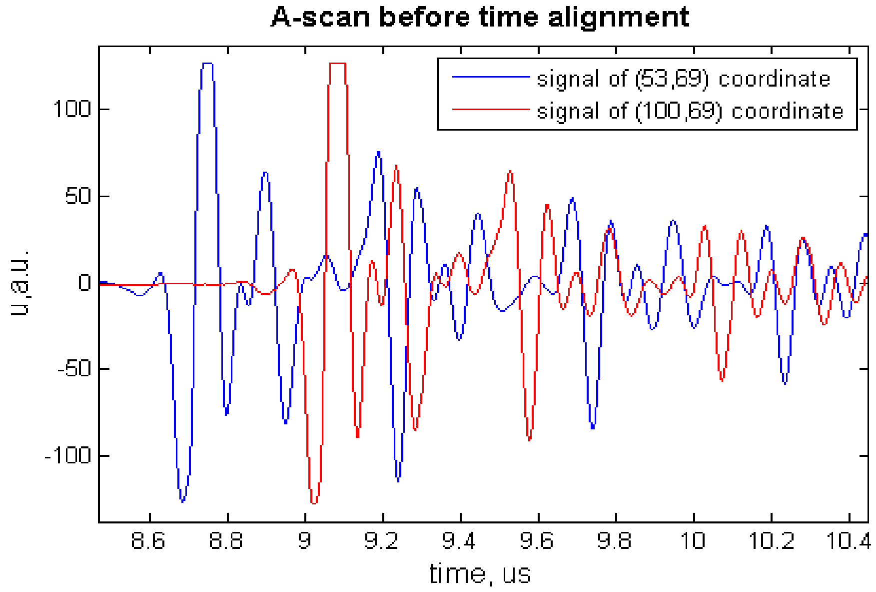

$$U(f) = \mathrm{FT}[u(t)];$$

$$U_F(f) = U(f) \cdot H(f);$$

$$u_F(t) = \mathrm{Re}(\mathrm{FT}^{-1}[U_F(f)]);$$



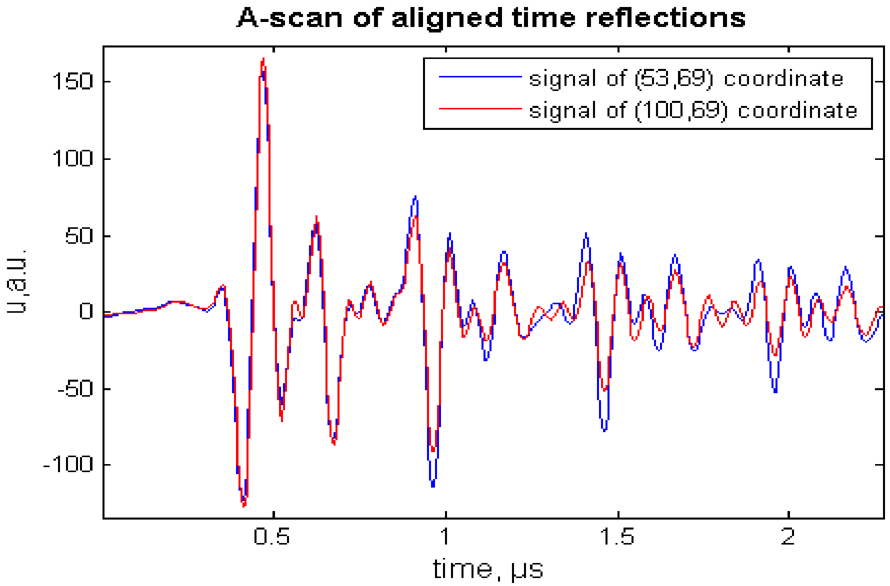
# Development of Post-processing Algorithm: Signal Filtering & Time Alignment

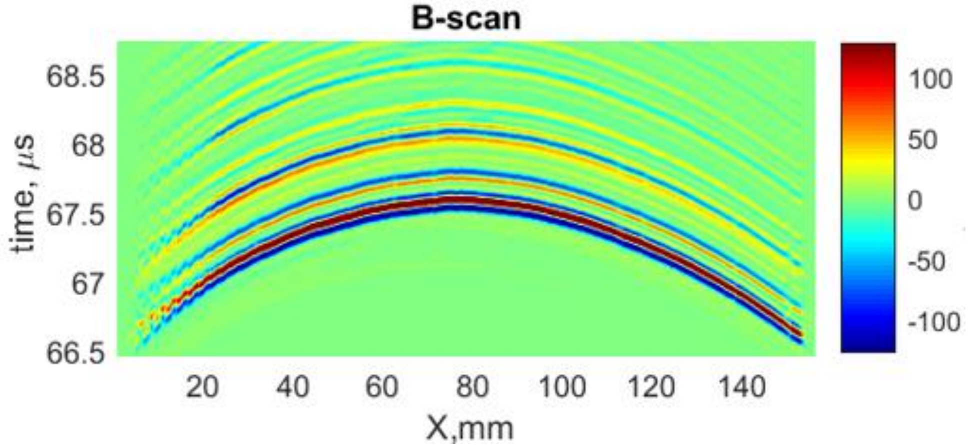


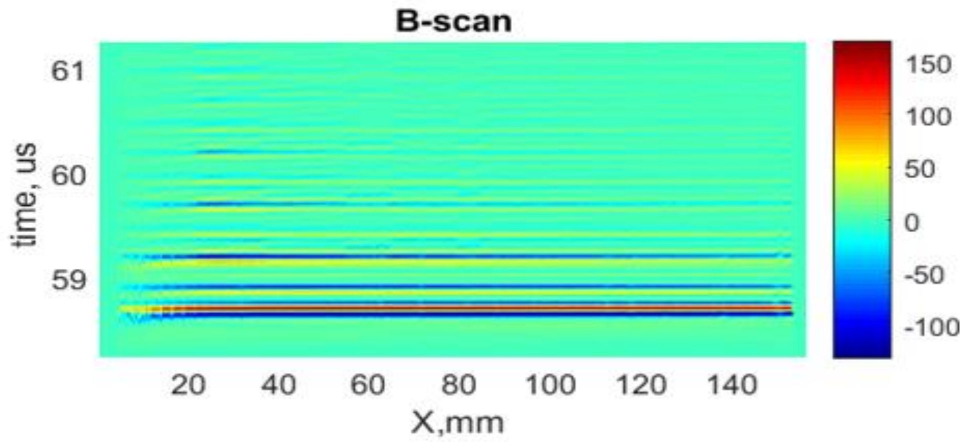

$$t_{n_1,k} = \min\{\arg[u_k(t_{n_1}) > U_{th}]\};$$

$$t_{0,k} = \min\{\arg\left[u_k(t_n) = 0\right]\};$$

$$u'_k(t_n) = u_k(t_n + t_{0,k});$$



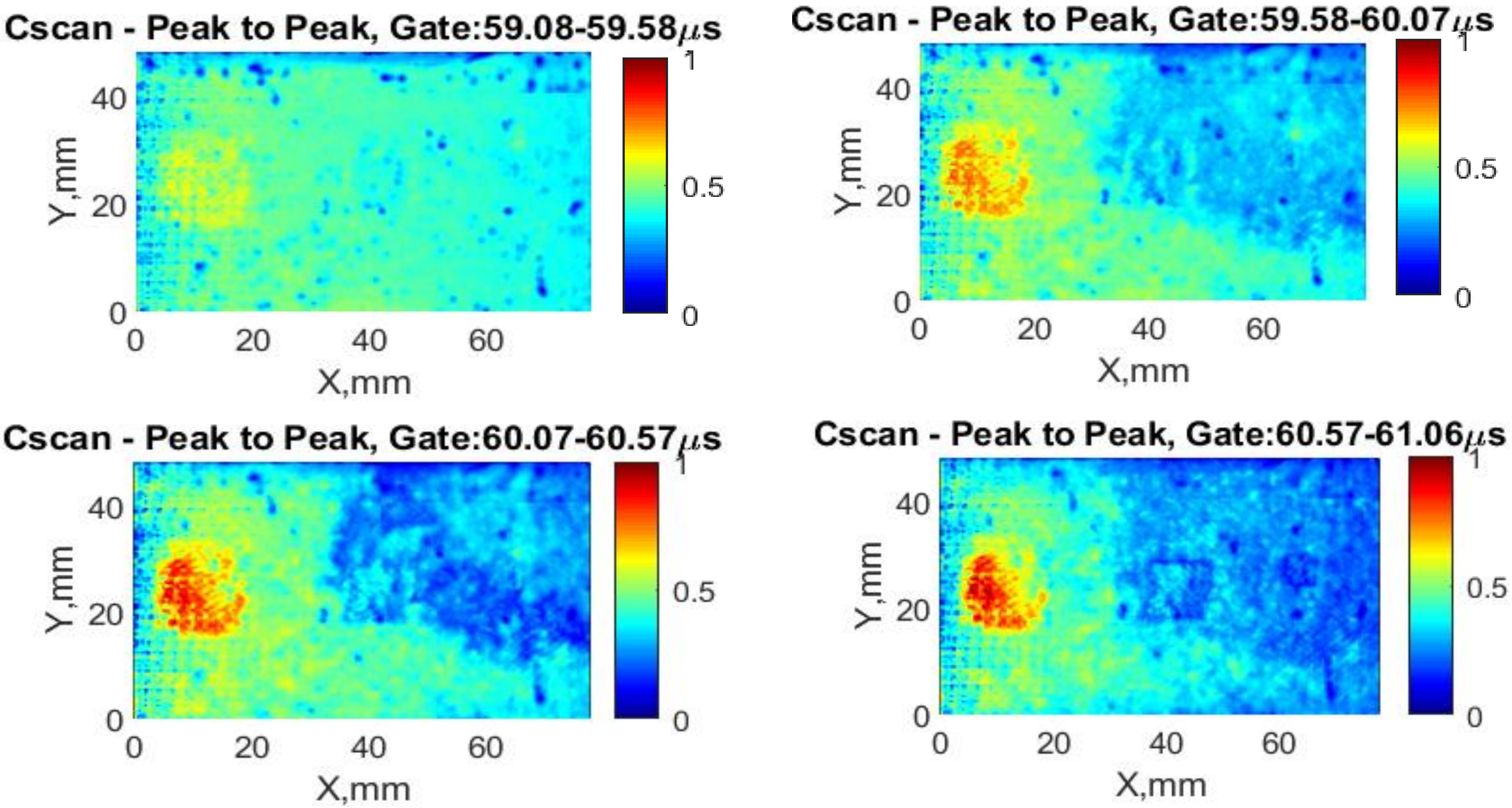
# Task 2: Determination & extraction of UT features capable to increase probability of defect detection

# Determination & Extraction of UT Features

Extracted features:

- Peak-to-peak amplitude at multiple interface reflections and at calculated time intervals where the maximum amplitude change occurs;
- Attenuation;
- Frequency domain maximum amplitude;
- Absolute energy;
- Frequency value at the maximum amplitude;
- Ratio coefficient of peak-to-peak amplitudes at certain time intervals.

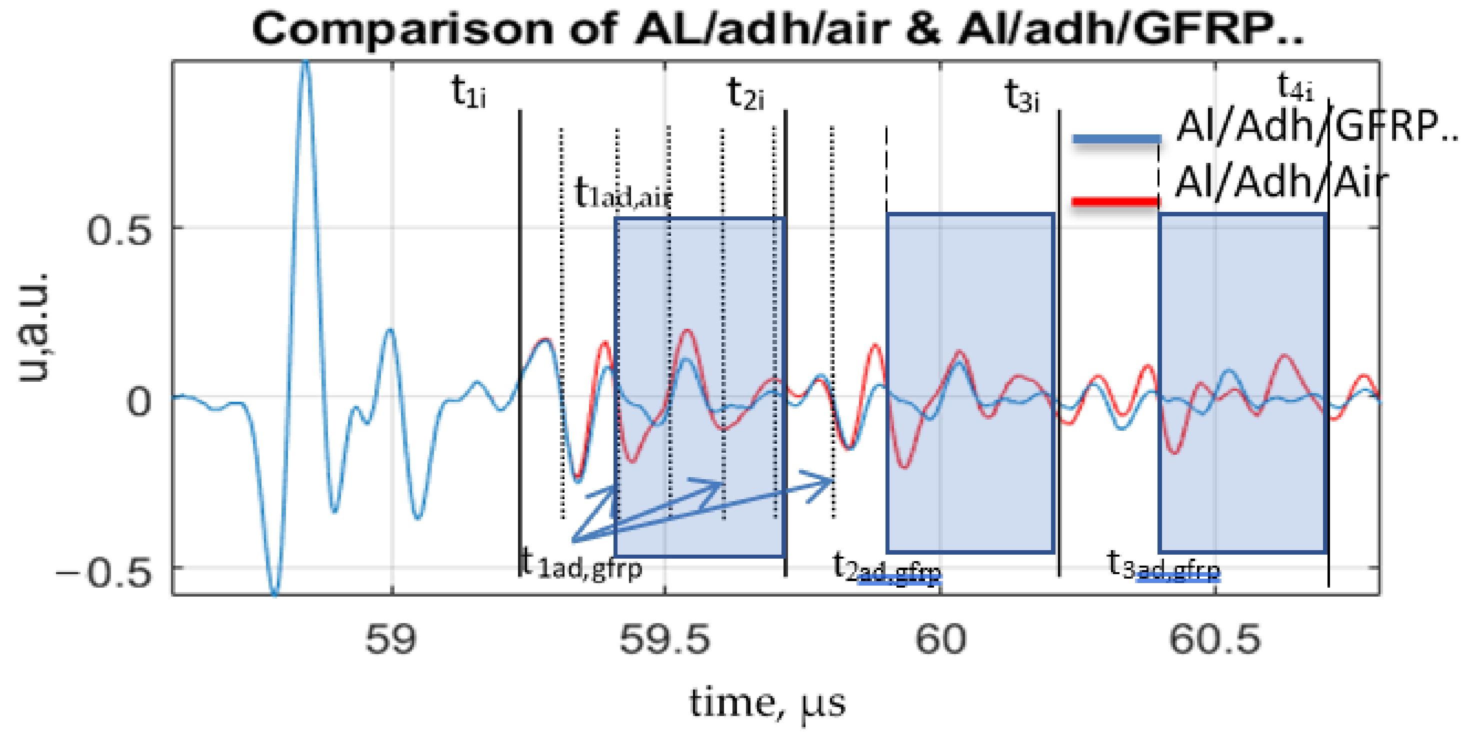
# UT Feature: Peak-to-peak amplitude at multiple interface reflections



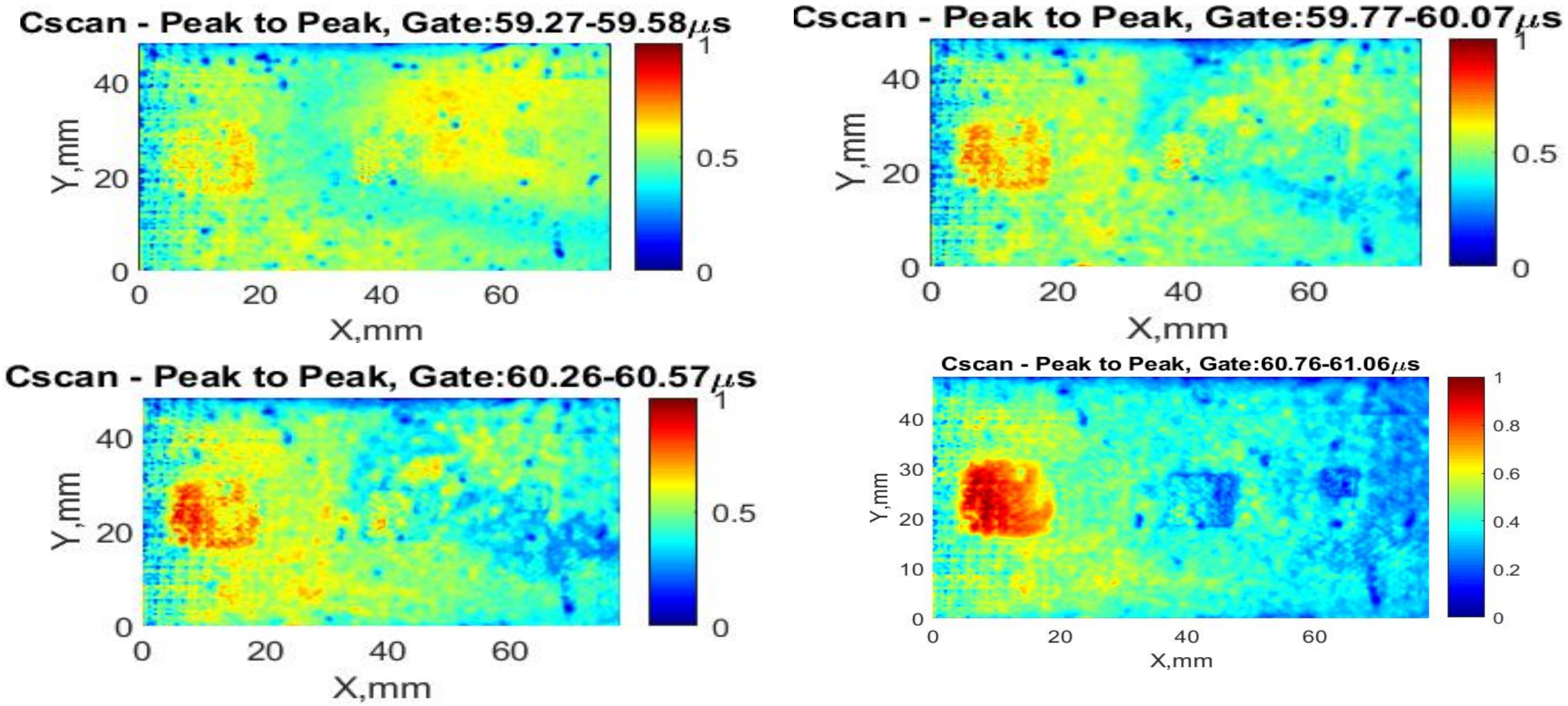
# UT Feature: Peak-to-peak amplitude at calculated time intervals where the maximum amplitude change occurs

Models of perfect bonding (aluminium-adhesive-composite) and debonding in the middle of adhesive layer (aluminium-adhesive-disbond) were created and signals $u(t)$ modelled:

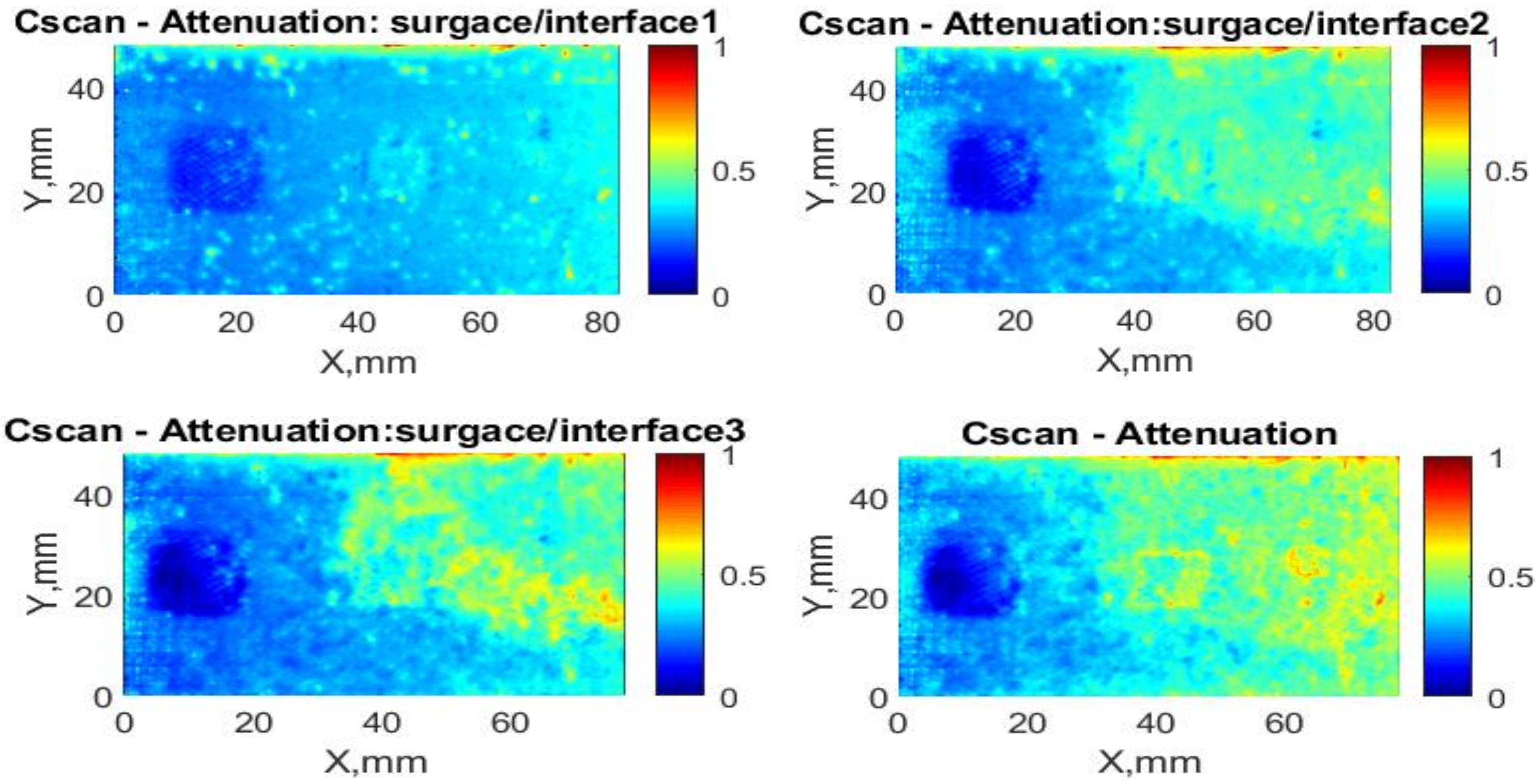
$$u(t) = y_{ref}(t) \otimes h(t);$$



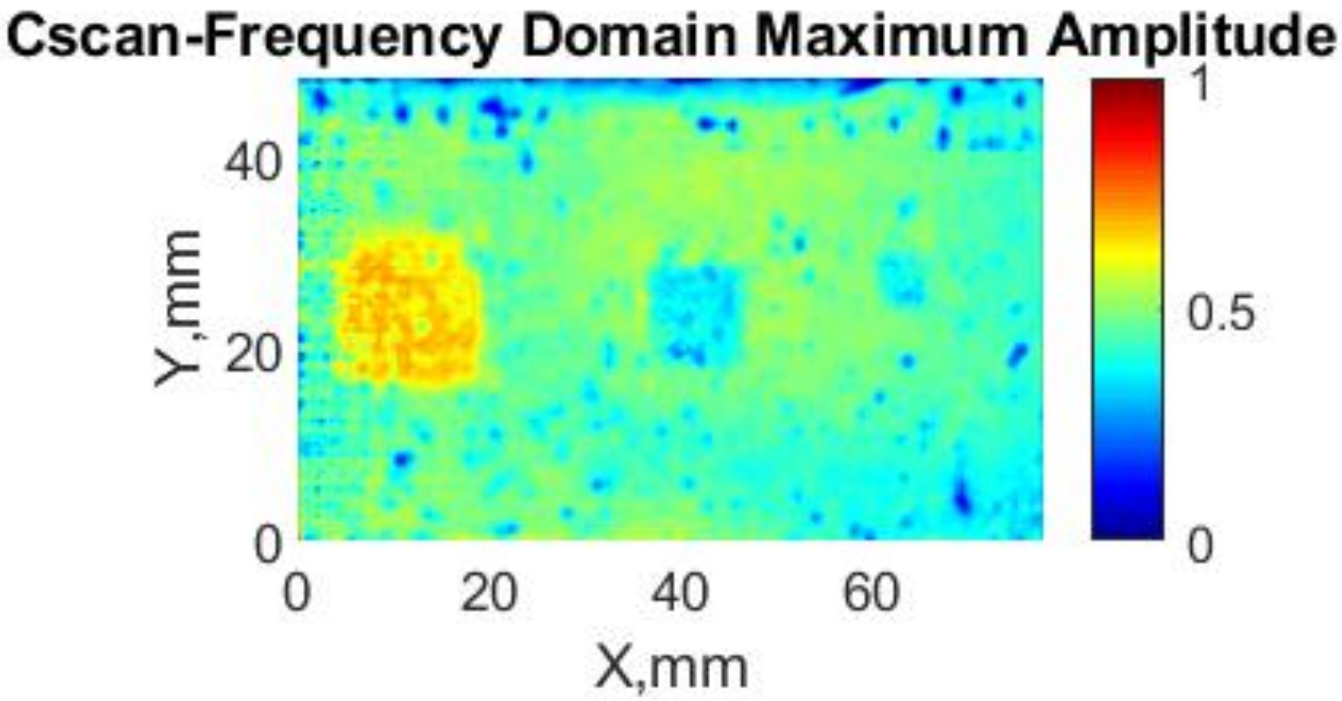
# UT Feature: Peak-to-peak amplitude at calculated time intervals where the maximum amplitude change occurs



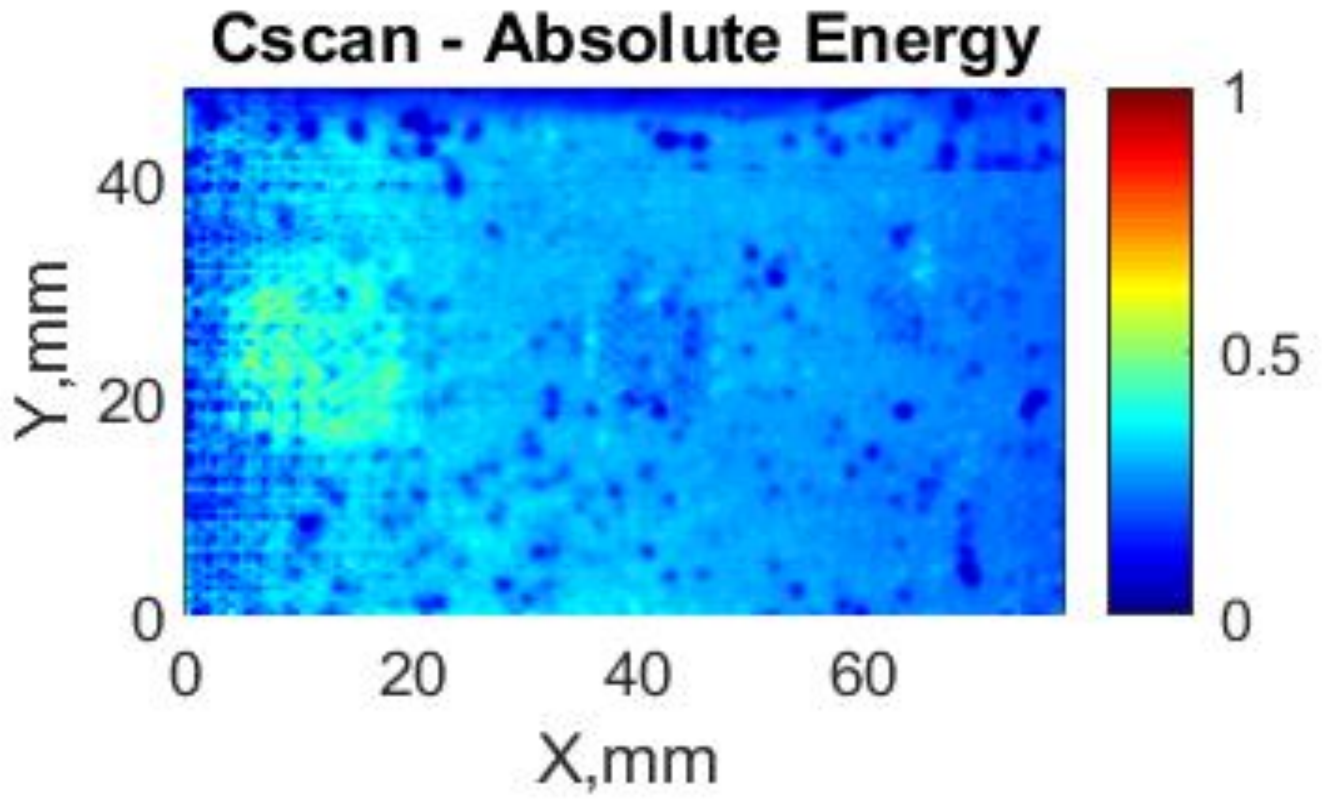
# UT Feature: Attenuation



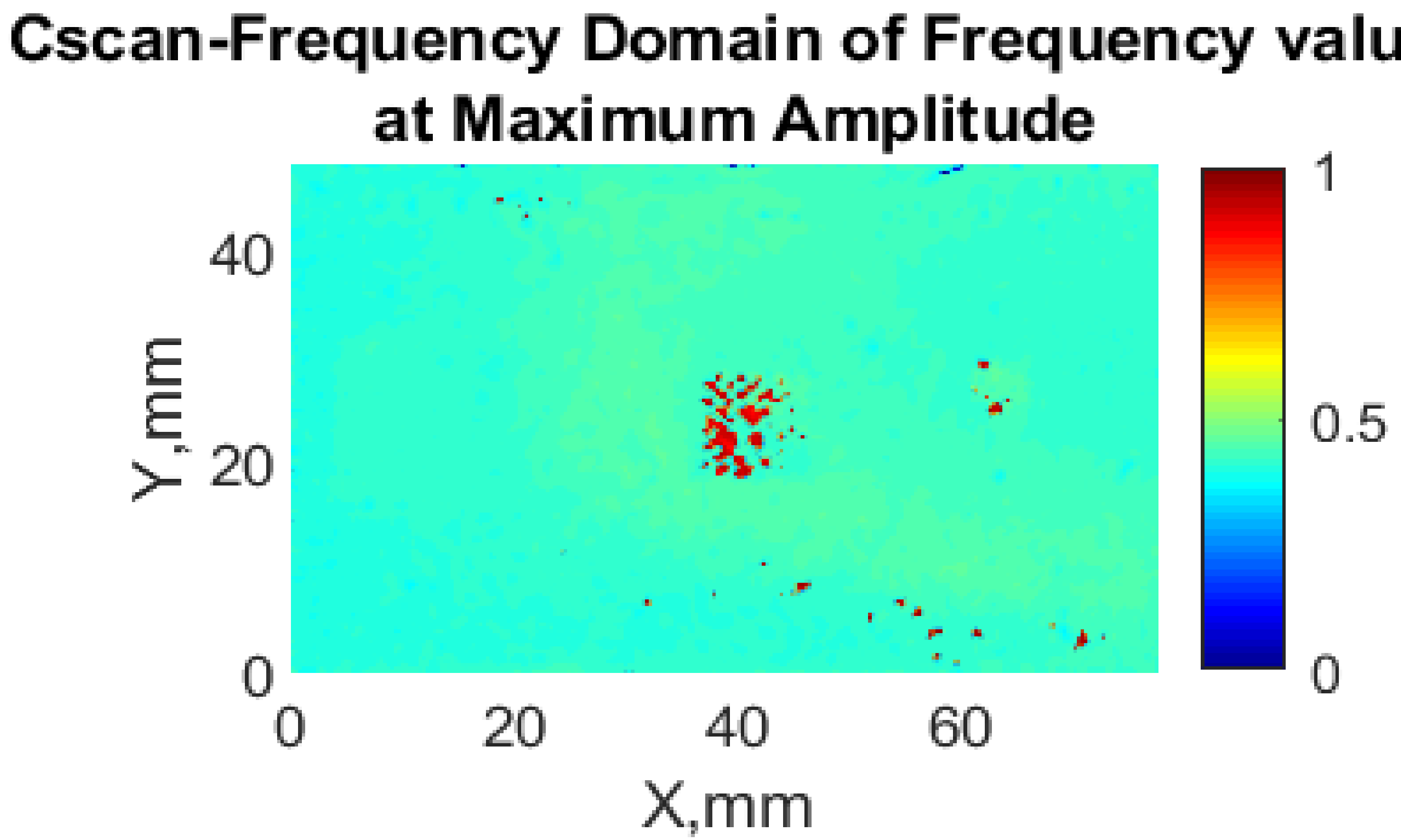
# UT Feature: Frequency domain maximum amplitude



# UT Feature: Absolute energy



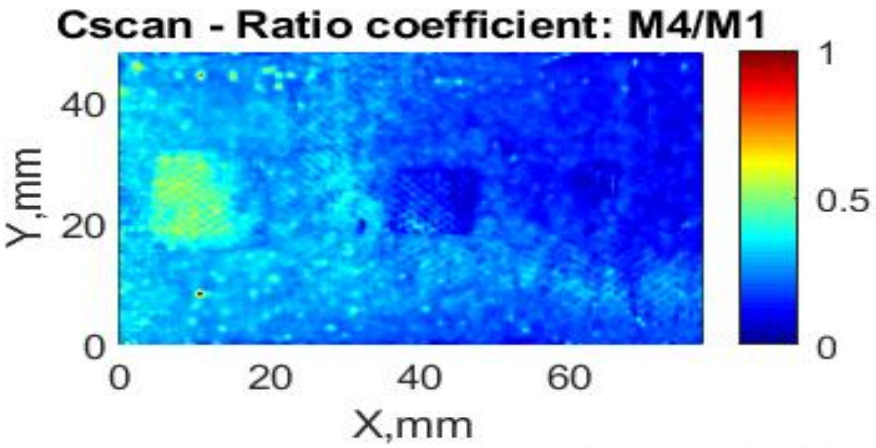
# UT Feature: Frequency value at the maximum amplitude

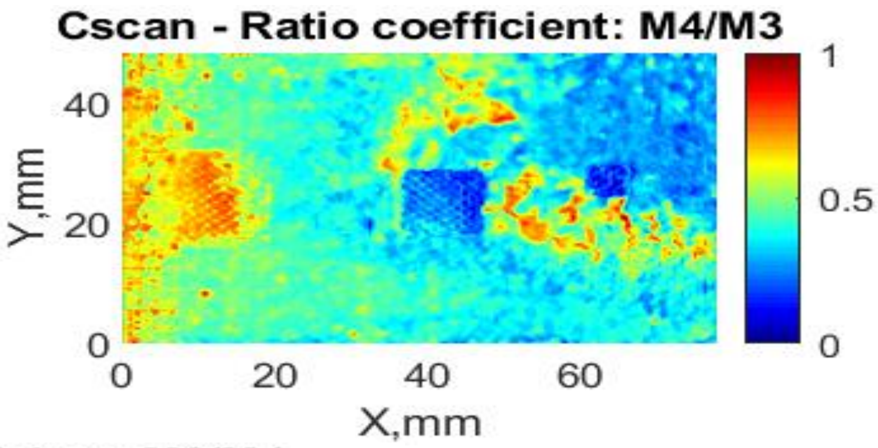


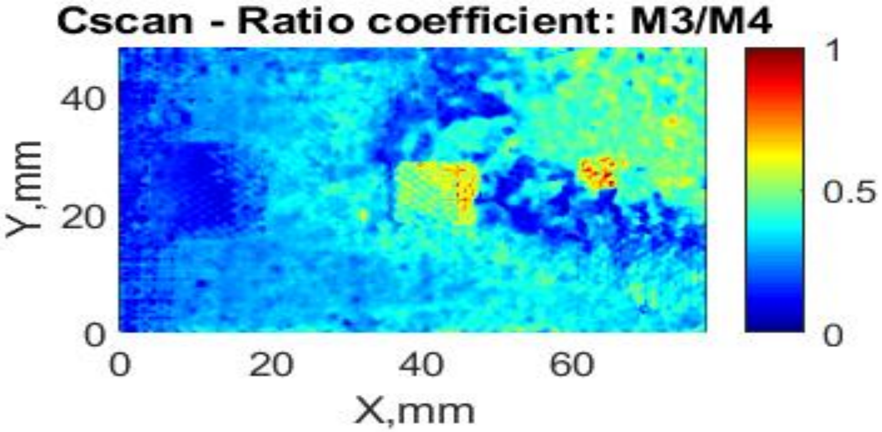
# UT Feature: Ratio coefficient of peak-to-peak amplitudes at certain time intervals

$$K_1 = \frac{M_n}{M_{n+1}};$$
$$K_2 = \frac{M_{n+1}}{M_n};$$

Ratio coefficients of peak-to peak amplitudes calculation:

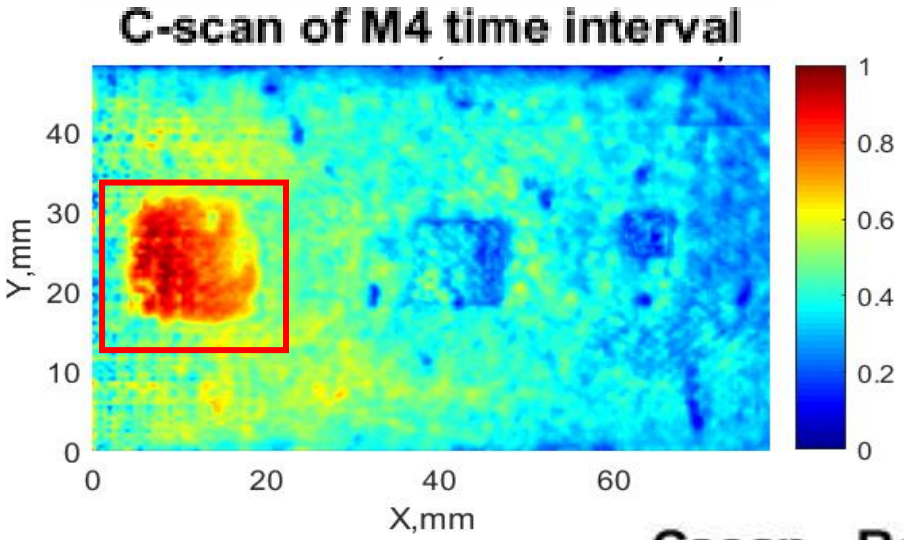


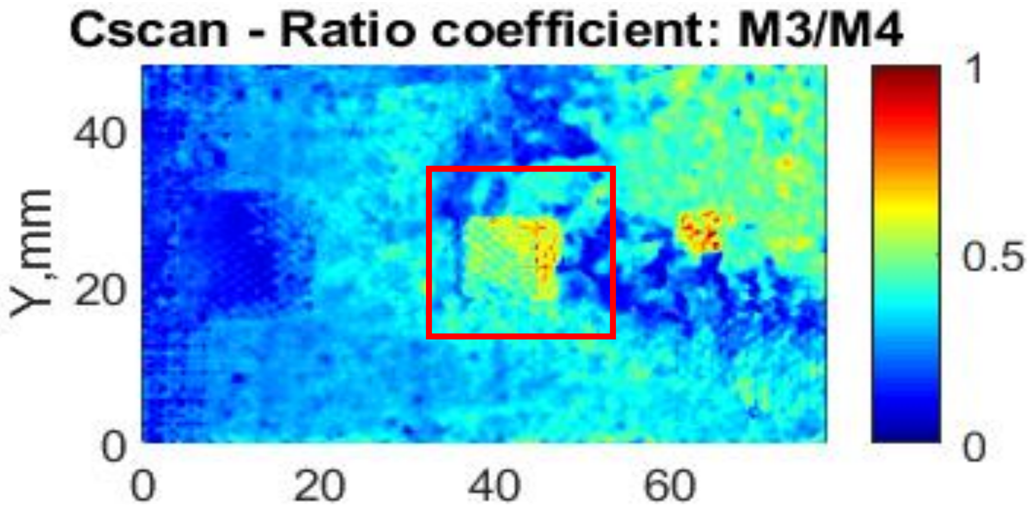



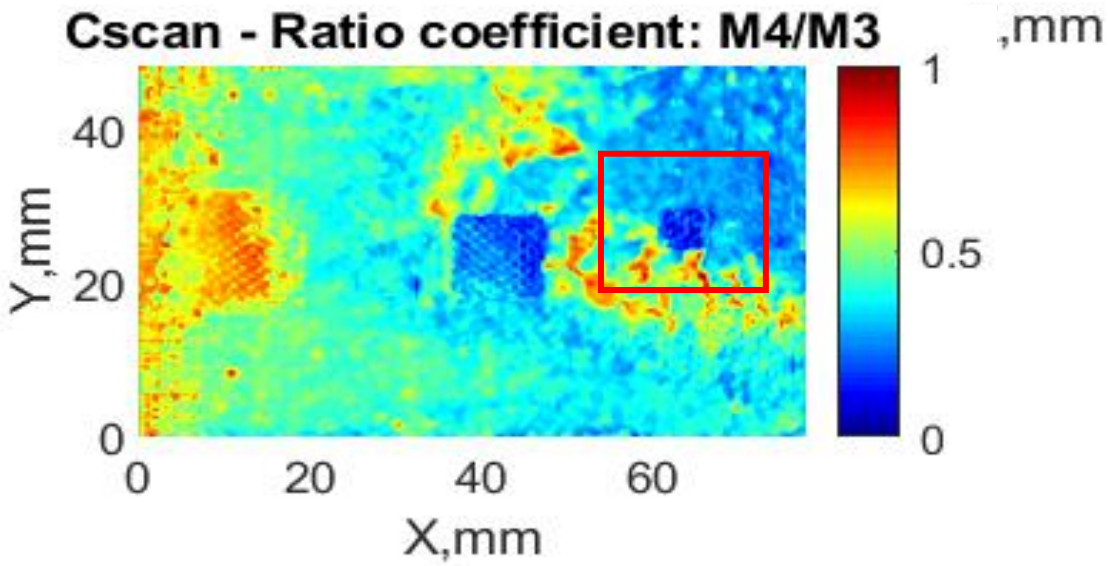



# Task 3: Evaluation of extracted features performance using -6dB threshold sizing method

# Performance Evaluation: Defect Sizing



# Performance Evaluation: Defect Sizing

| Interface reflection | Slice along | Big defect size, mm | Medium defect size, mm | Small defect size, mm |
|---|---|---|---|---|
| **M4** | X axis | 16.5 | 3.4 | 2.05 |
| **M4/M1** | X axis | 9.8 | - | - |
| **M4/M3** | X axis | 11.6 | 11.5 | 4.9 |
| **M3/M4** | X axis | 13.6 | 10.3 | 3.8 |

# Future Plans

- Data fusion of C-scans received from different extracted features;
- Development of post-processing technique including artificial intelligence for automatic analysis of UT data and elimination of influential factors.

# Conclusion: Steps of UT Data Analysis

1. Investigation of fundamentals of wave-disbond interactions;
2. Quantitative evaluation to study wave propagation in the structure;
3. Qualitative evaluations to determine factors influencing defect detection;
4. Determination of UT features capable to increase evaluation performance and to be used in post-processing technique;
5. Development of post-processing algorithms to eliminate influential factors and extract UT features;
6. Verification and comparison of evaluation performance for extracted features;
7. Development of logical loops in processing algorithm to make it more automatized.