Corrosion-Based Defect Detection and Classification in Pipe Wall Using Multiple High Order Ultrasonic Guided Wave Modes

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Abstract: Metal loss due to corrosion can lead to dangerous accidents in pipeline systems. To avoid any leakage of toxic materials into environment from pipeline network structures, reliable non-destructive evaluation techniques to detect early stage of potentially dangerous defects are required. In general, classic NDT methods enables to detect almost all types of dangerous defects however they are time and cost consuming as requires large areas to be scanned. On the other hand, long range ultrasonic methods enable fast screening of large areas of the pipe by assessing corrosion level, however they tend to fail detecting concentrated small defects. Hence intermediate methods are required which are fast and sensitive to small, concentrated defects such as pitting. Recently, novel inspection techniques used higher order guided wave modes that are more sensitive to concentrated corrosion defects, but they still have limited inspection coverage and varying sensitivity to defects of different type. The objective of this work was to investigate higher order modes for different defect types and to propose new medium range corrosion screening approach in circumference of the pipe based on selective generation of high order guided wave modes. The selection of wave modes suitable for detection of various corrosion type defects is discussed with support of in-plane and out-of-plane distributions, leakage losses due to liquid load and dispersion curves. The analysis led to highest potential of combination of S3 and A1 wave modes for various type defect detection. Selective excitation of desired modes was demonstrated through finite element simulations and confirmed with experiments, showing the ability to generate modes of interest while supressing the co-existing waves. Interaction between the selected wave modes and corrosion type defects was investigated both by finite element simulations and experiments. It was found that selected wave modes are sensitive to various types of corrosion defects like pitting, localised, distributed corrosion and ensures sufficient propagation distance. It was demonstrated that such new inspection technique unravels high potential for machine learning and/or artificial intelligence assistance for defect detection and classification according to the type of defect.

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CORROSION BASED DEFECT DETECTION AND CLASIFICATION IN PIPE WALL USING MULTIPLE HIGH ORDER ULTRASONIC GUIDED WAVE MODES

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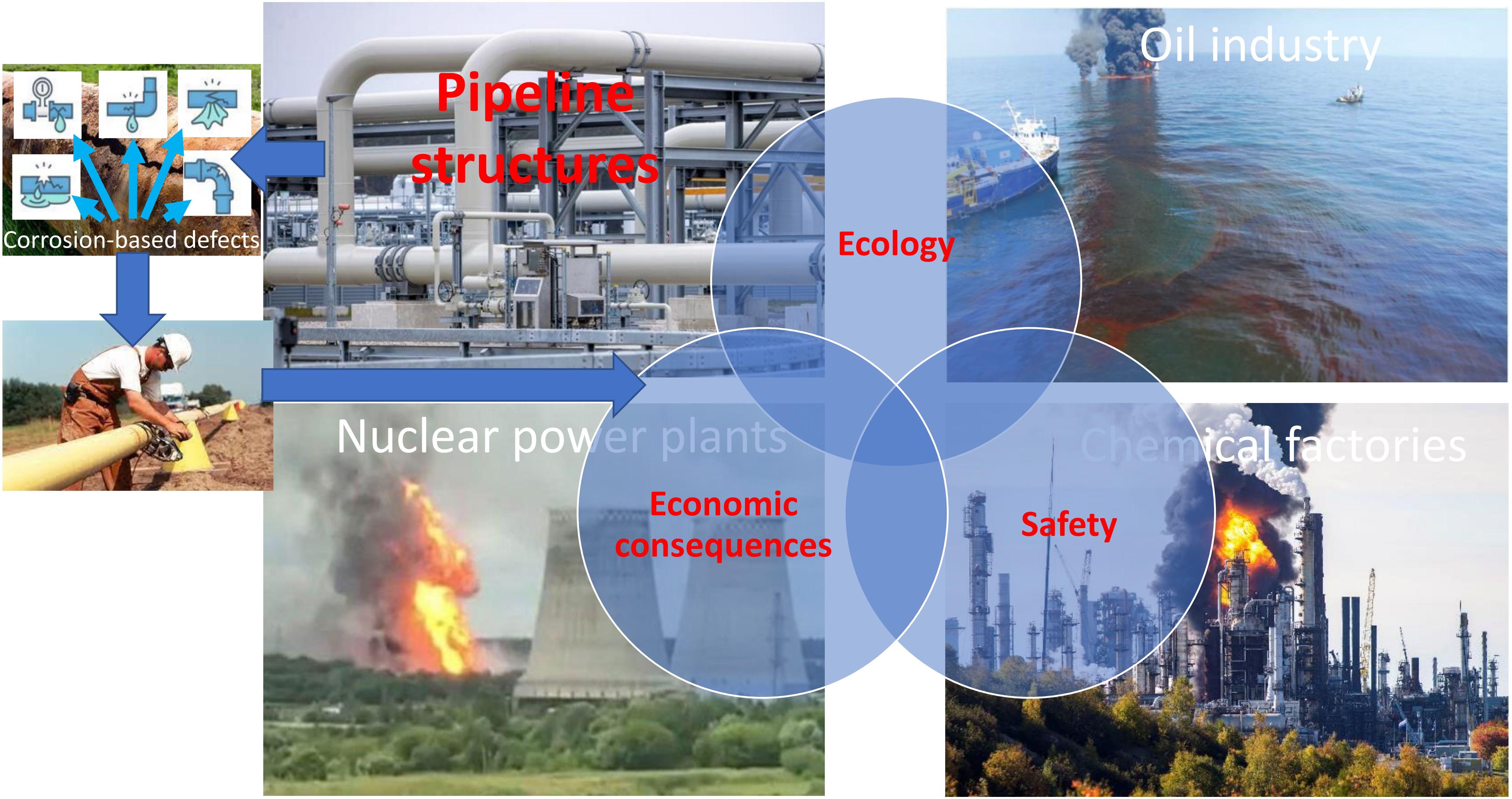
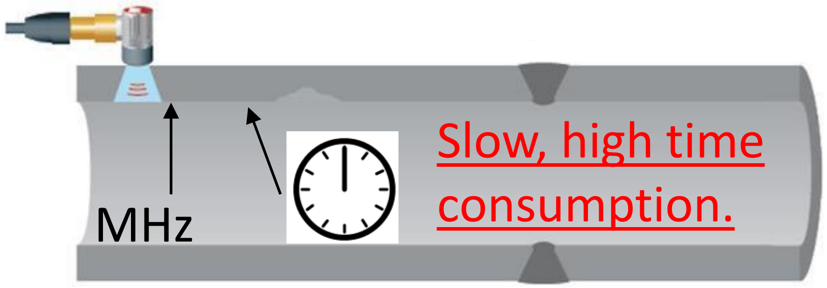
Object


Corrosion-based defects
Pipeline structures
Oil industry
Nuclear power plants
Chemical factories
Ecology
Economic consequences
Safety

There are essentially only two methods!

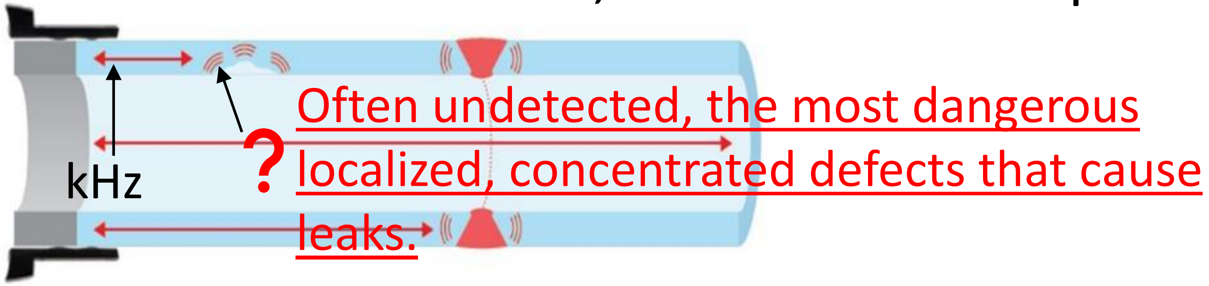
Local inspection



High frequencies, sensitive to defects.

Long range inspection

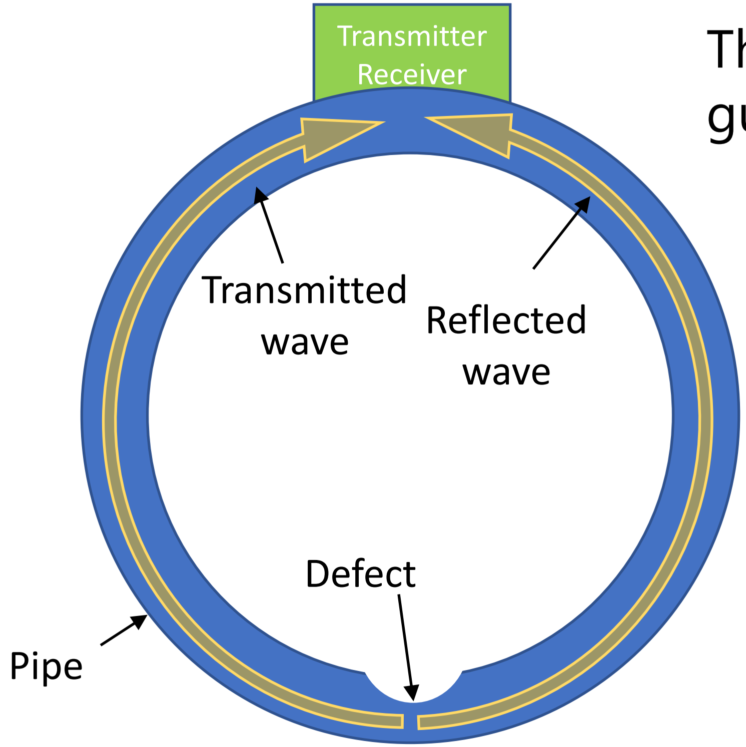
Large surface area. Fast, low time consumption.



Low frequencies.

Objective of the work: To develop and investigate a relatively fast and sensitive ultrasonic guided wave measurement method for detecting and identifying corrosion damage in pipelines, particularly focusing on localized and concentrated defects.

Hypothesis: There exist specific guided wave modes and specialized signal processing methods that would allow the detection and recognition of localized corrosion defects in cross-sectional measurements of the pipe at a single point, avoiding the scanning the entire pipe circumference.



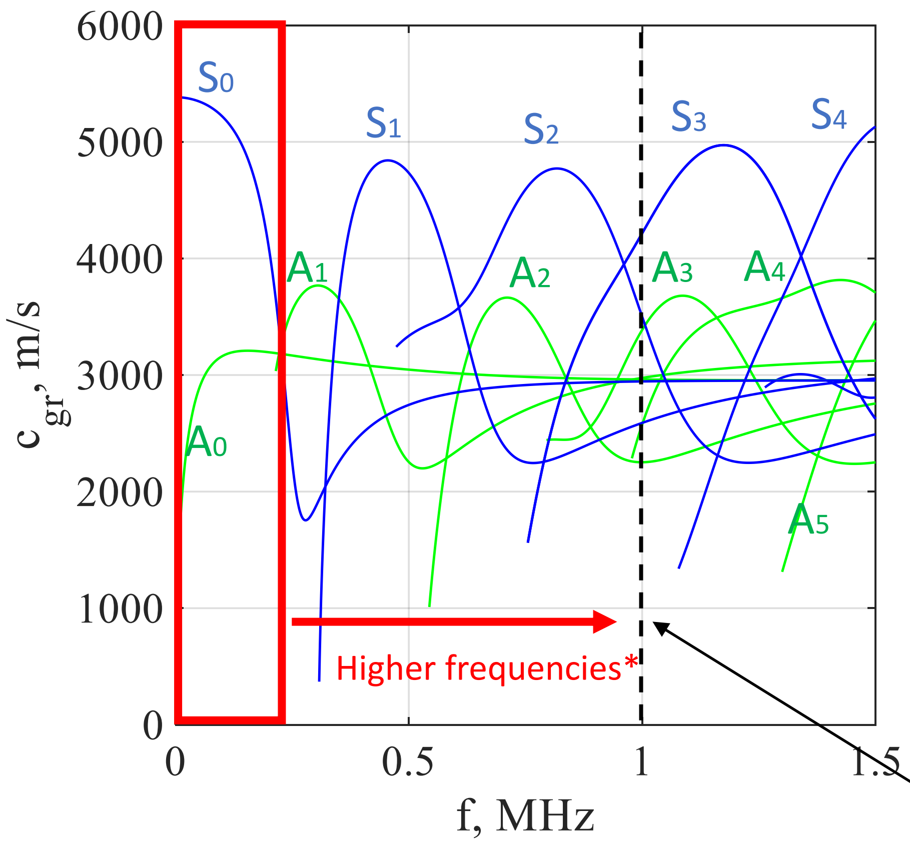
Proposed method

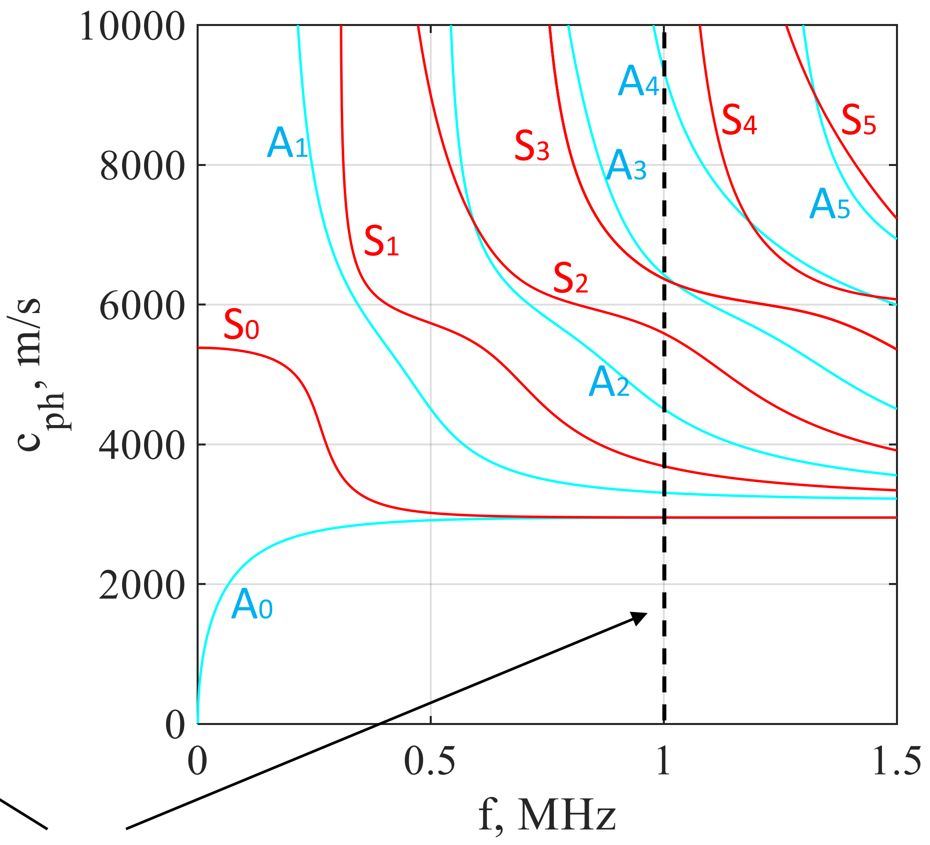
The medium-range method is based on the measurement of higher-order guided wave modes in the cross-sectional plane of the pipe.

Scientific problems

* How to excite, seperate, and measure higher-order modes?
* What is the possible measurement distance, and how is it influenced by the pipe fillings with liquids?
* Are these modes influenced by corrosion defects, and if so, how?
* How does the pipe filling affect defect detection?
* How are higher-order modes influenced by different types of defects?
* Can they potentially enable the detection and classification of defects based on their type?

Existing modes (9mm steel alloy)





9 existing modes

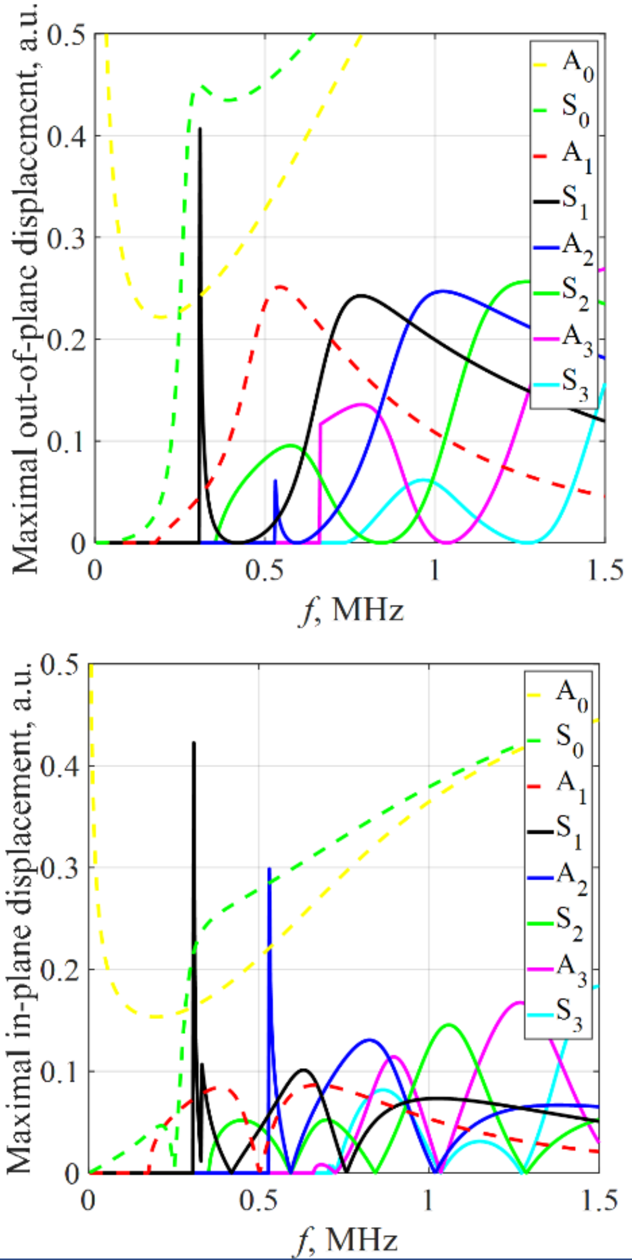
- Frequency
- Propagation velocity
- Excitation efficiency
- Propagation losses

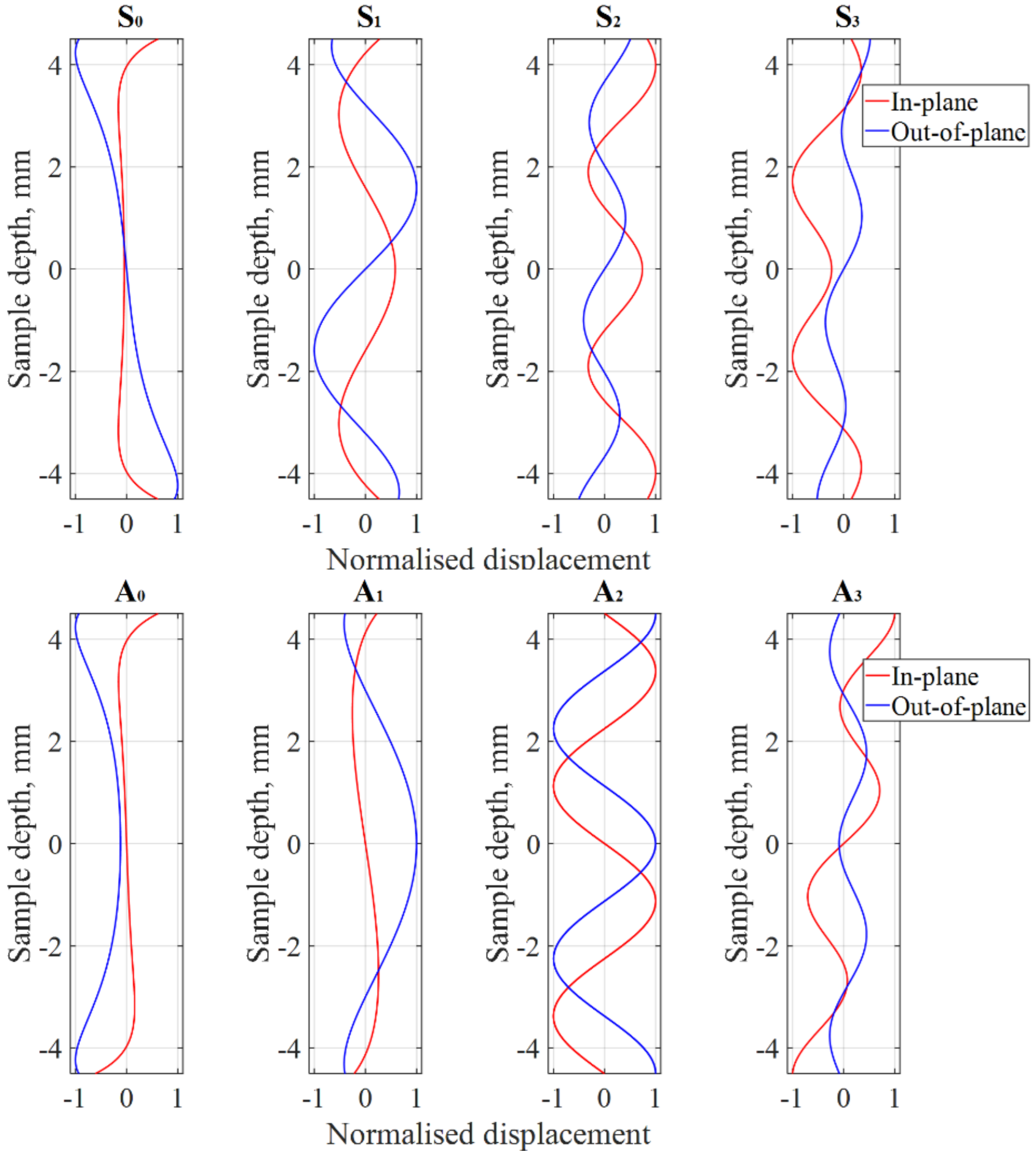
Selection of suitable modes - investigation of excitation capabilities

Normal component

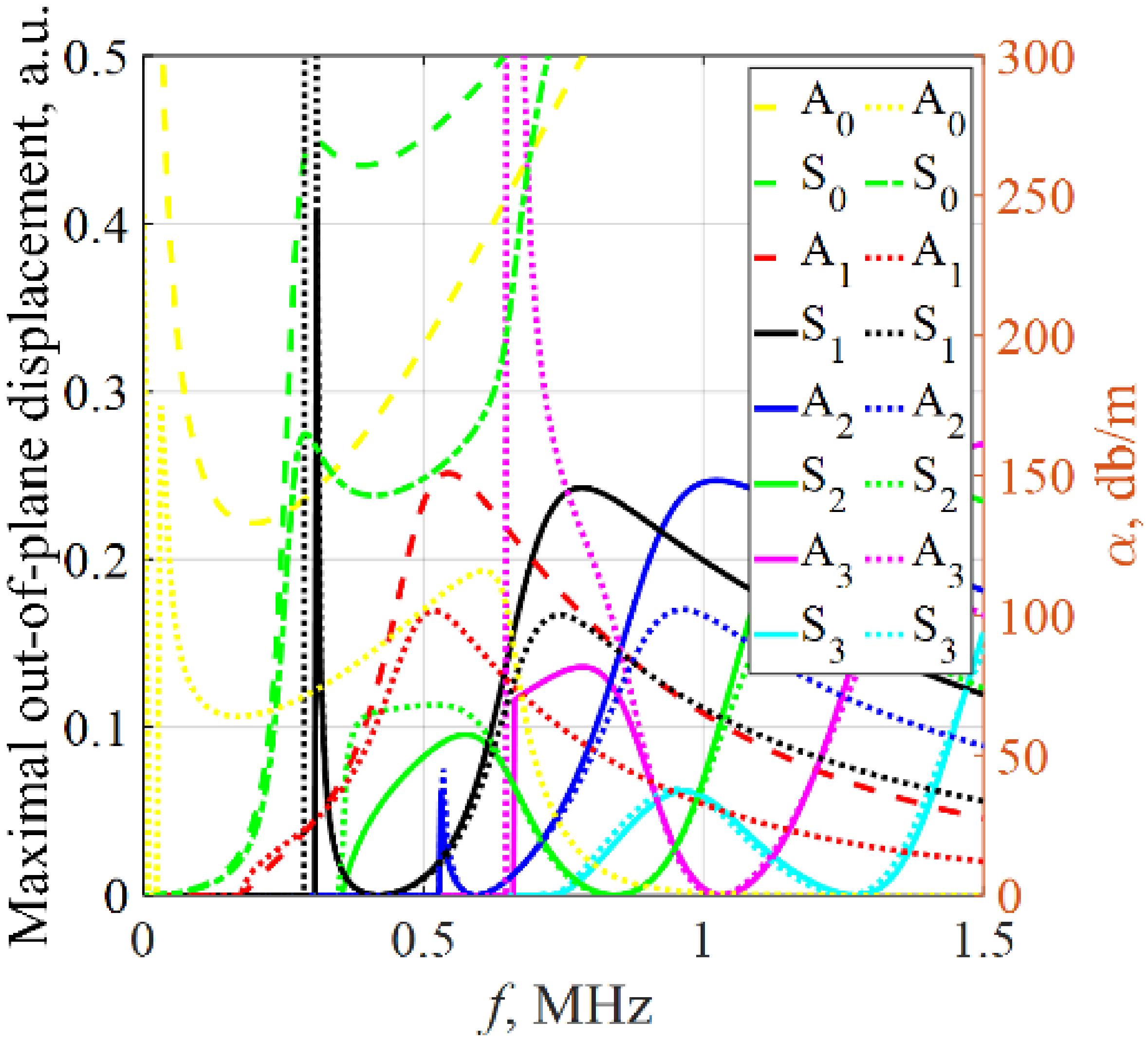
Losses?

Tangential component



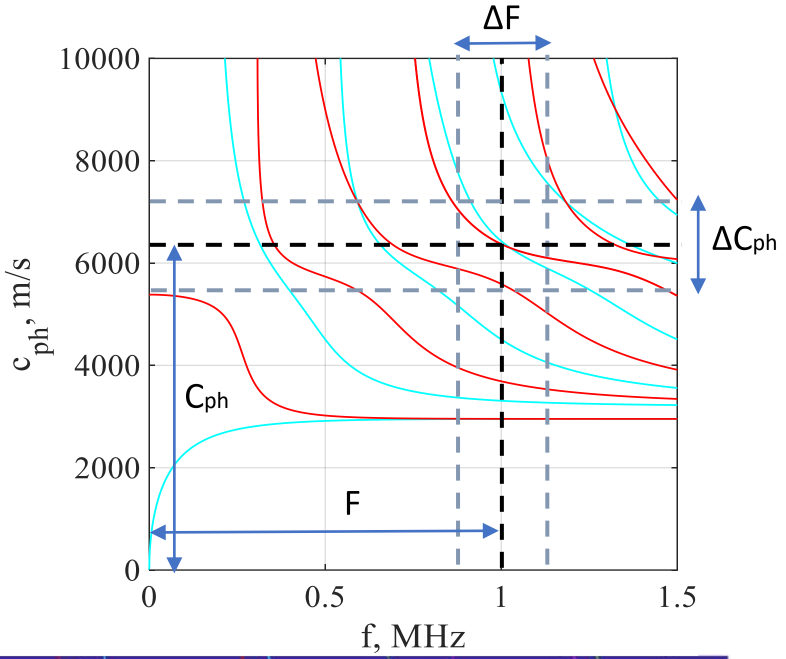


Selection of suitable modes - propagation losses.



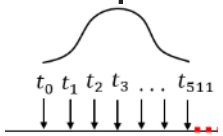
1 MHz					
Moda	C_{ph}(m/s)	C_{gr} (m/s)	λ (mm)	u (n.u.)	α, (db/m)
A_3	6586	3206	6.59	0.0	1
S_3	6458	**4048**	6.46	0.06	**34**
A_2	4623	2260	4.62	0.25	100
S_2	5667	3784	5.67	0.07	40
A_1	3318	2959	3.32	0.11	**33**
S_1	3729	2254	3.73	0.2	67
A_0	2951	2963	2.95	0.62	-
S_0	2955	2944	2.96	0.65	457

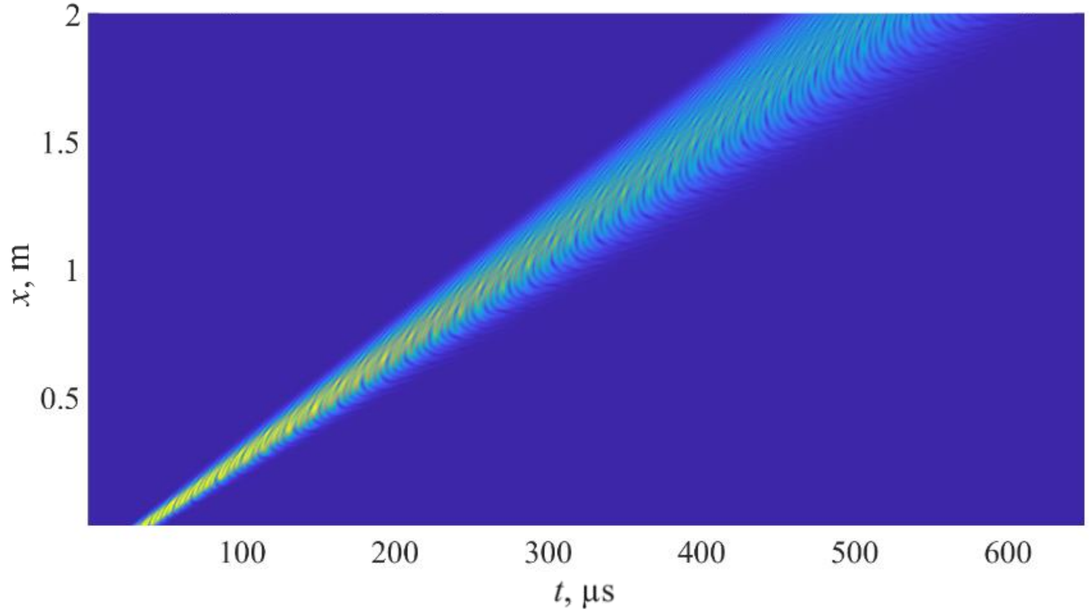
Investigation of excitation capabilities for the selected modes in a finite element model.

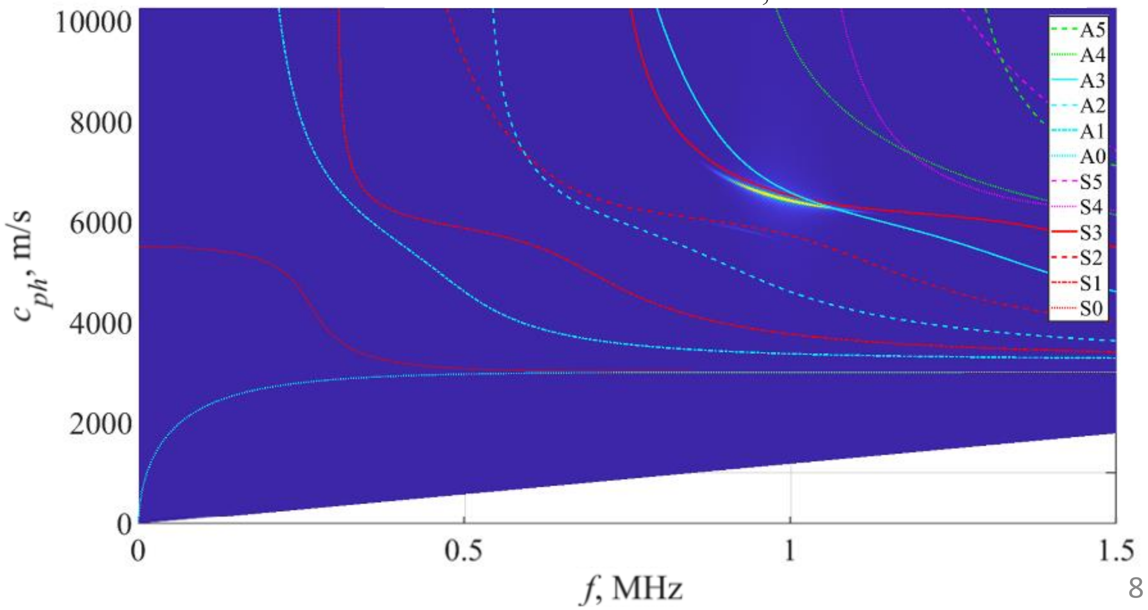


Investigating the influence of parameters on the excitation of the selected mode

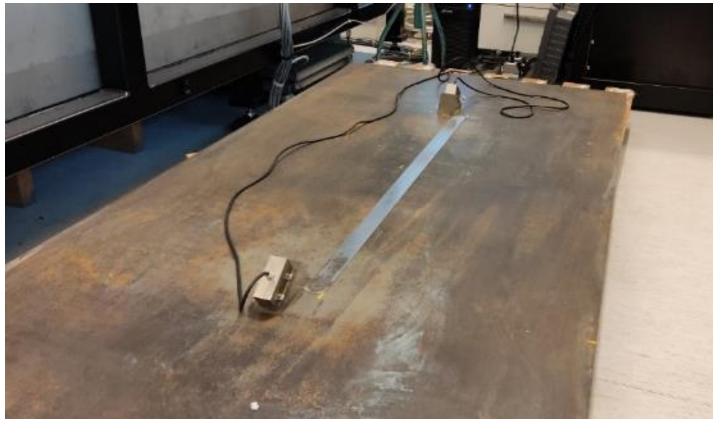
- Central frequency [F].
- Bandwidth [ΔF].
- Aperture [ΔCph].
- Excitation by phase velocity of a specific mode [Cph].
- Spatial spectrum smoothing.



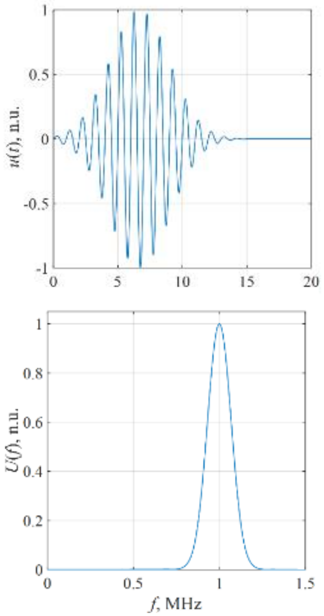


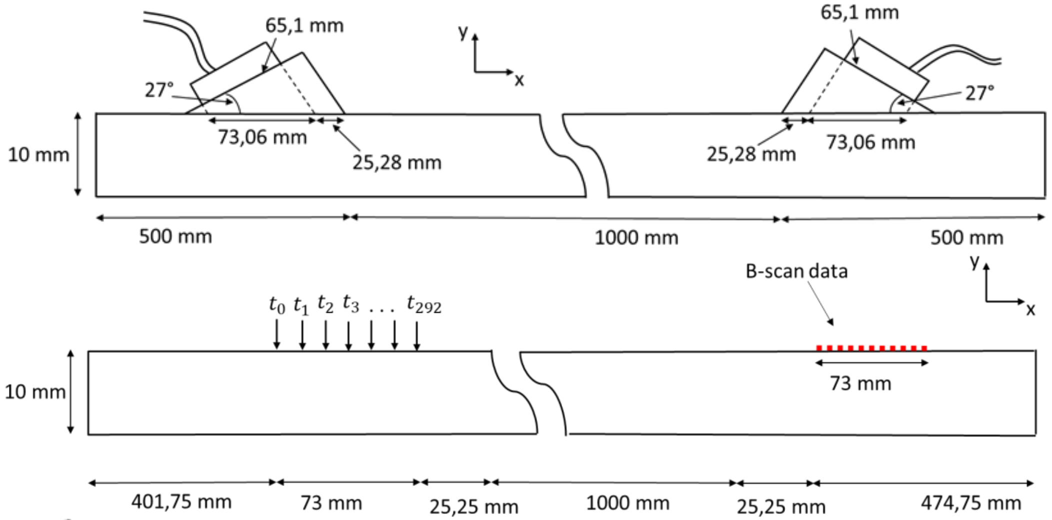


Experimental verification of selective excitation



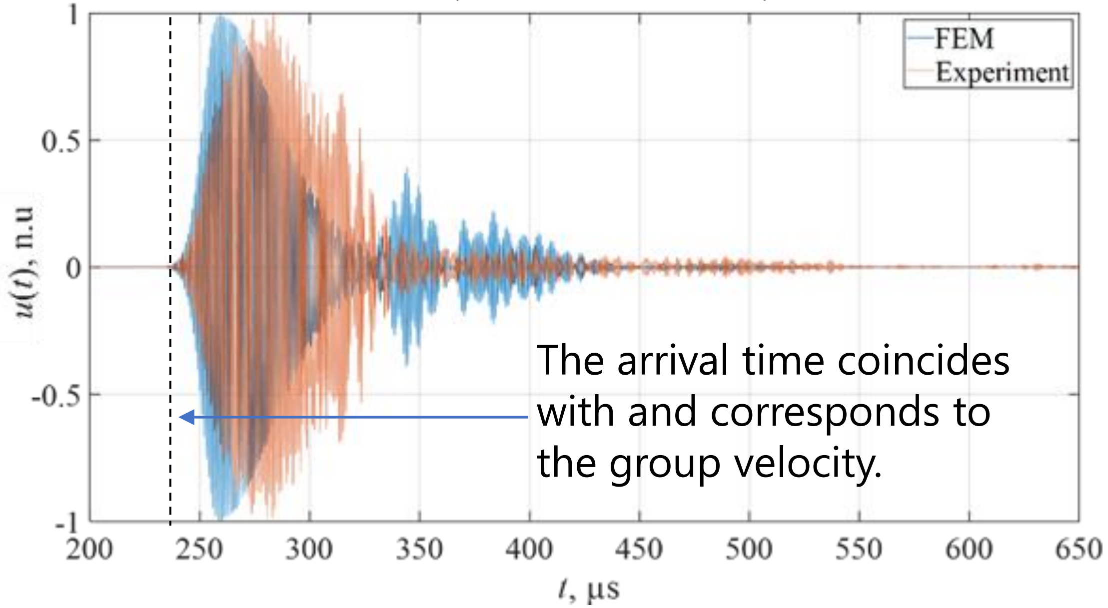
Phased array transducer:
CdC9463-2 A101 (HY)
Elements: 32
Element pitch: 2,05 mm
Aperture: 65,1 mm
Organic glass prism: 27°





Experiment

FEM

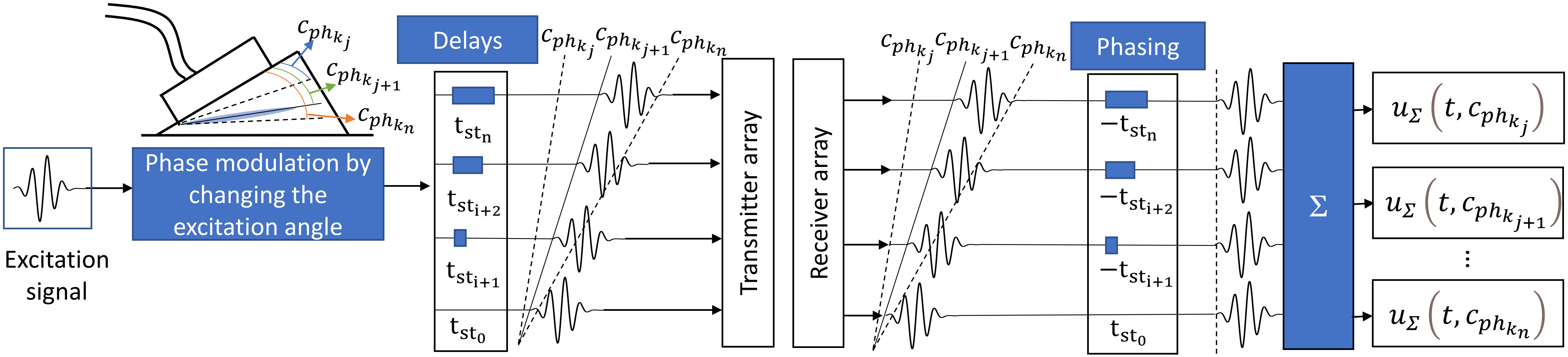


The arrival time coincides with and corresponds to the group velocity.

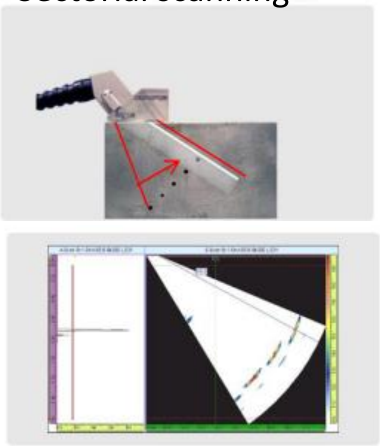
The identified patterns are quite general and applicable for adjusting frequencies in pipes with different parameters.

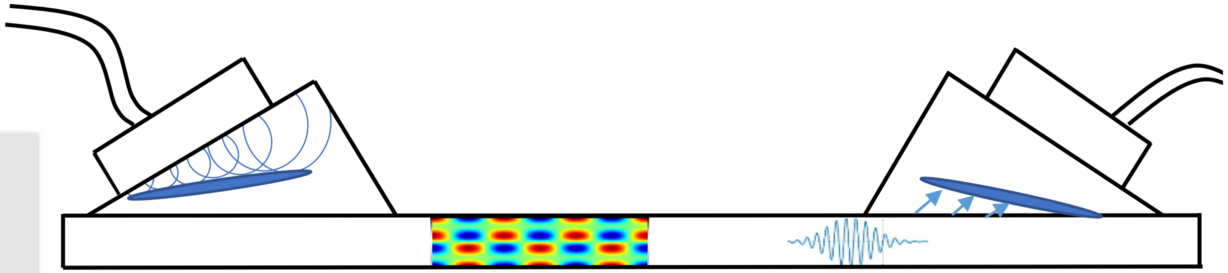
https://doi.org/10.3390/met12030503

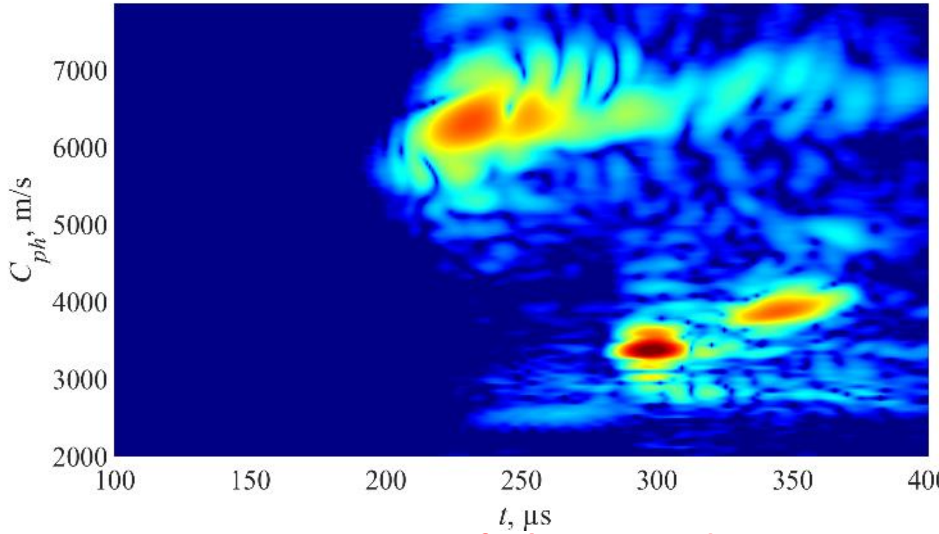
Method of mode excitation and signal processing



Sectorial scanning





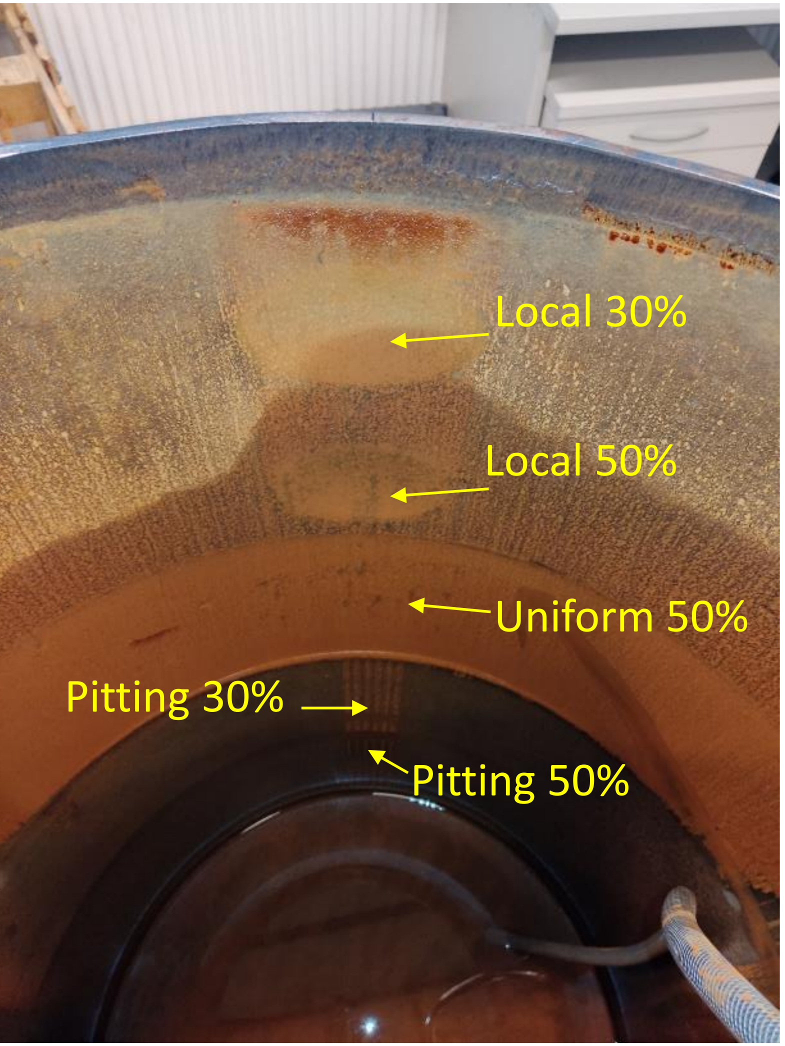


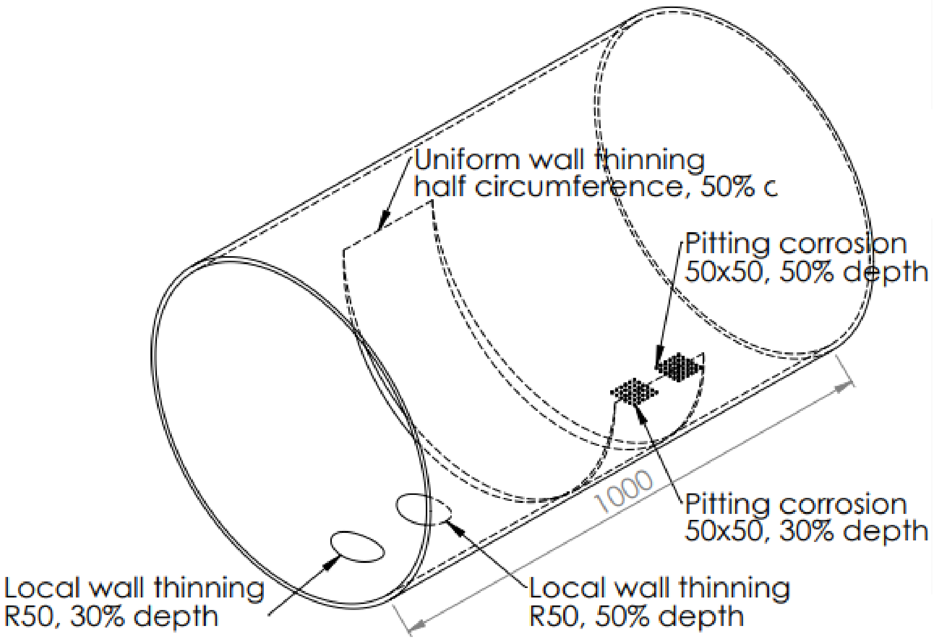
A new method has been proposed for the excitation and analysis of multimodal signals at a single point without the need for additional mechanical scanning

A new type of ultrasound imaging has been introduced

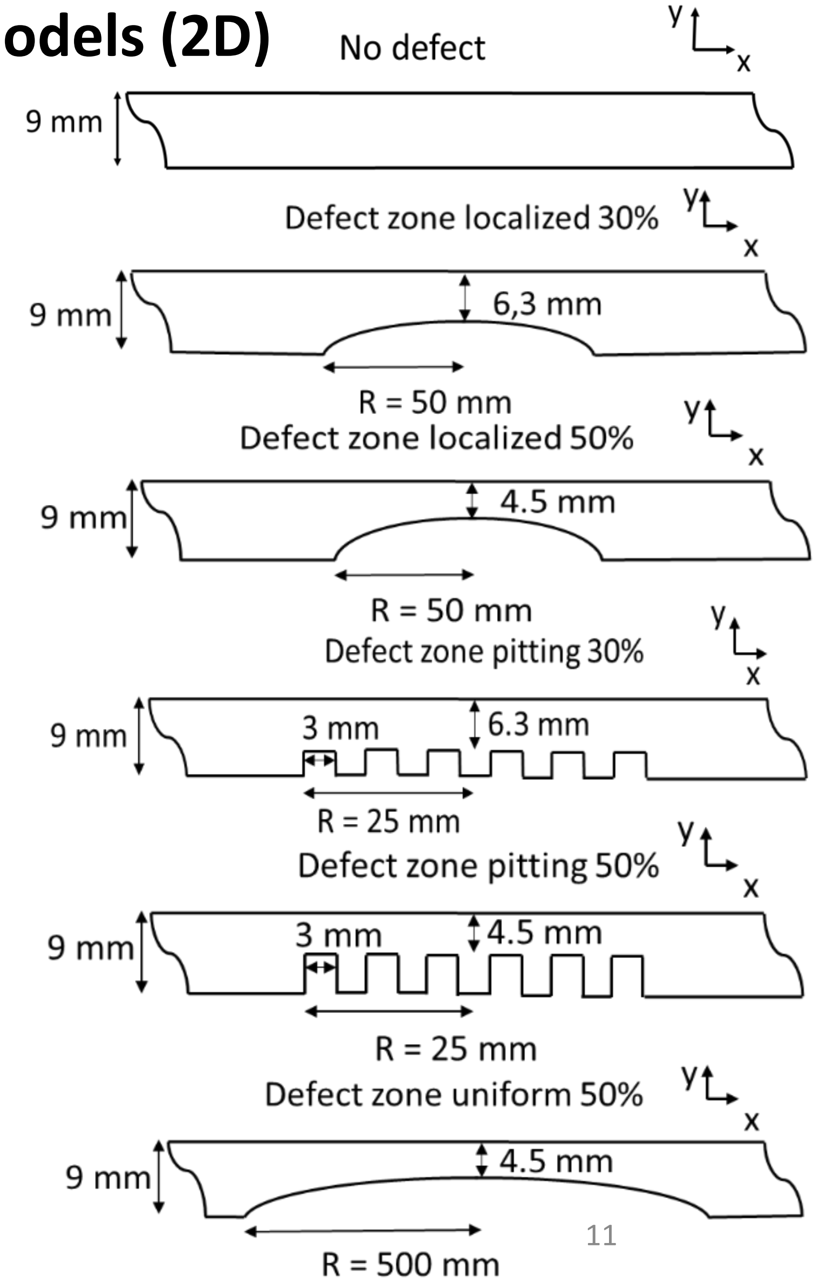
Artificial defects simulating corrosion in the specimen and the Finite Element Model (FEM).

Experiment



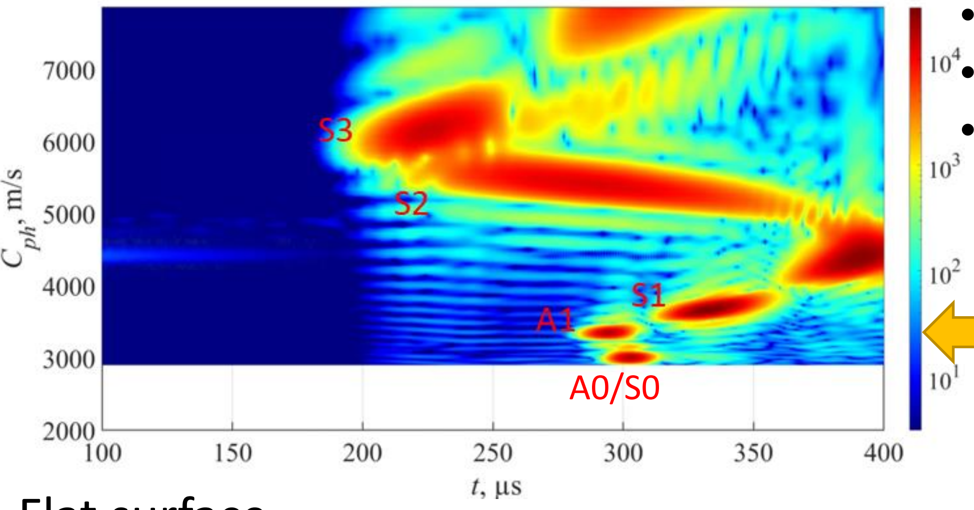


Finite element models (2D)

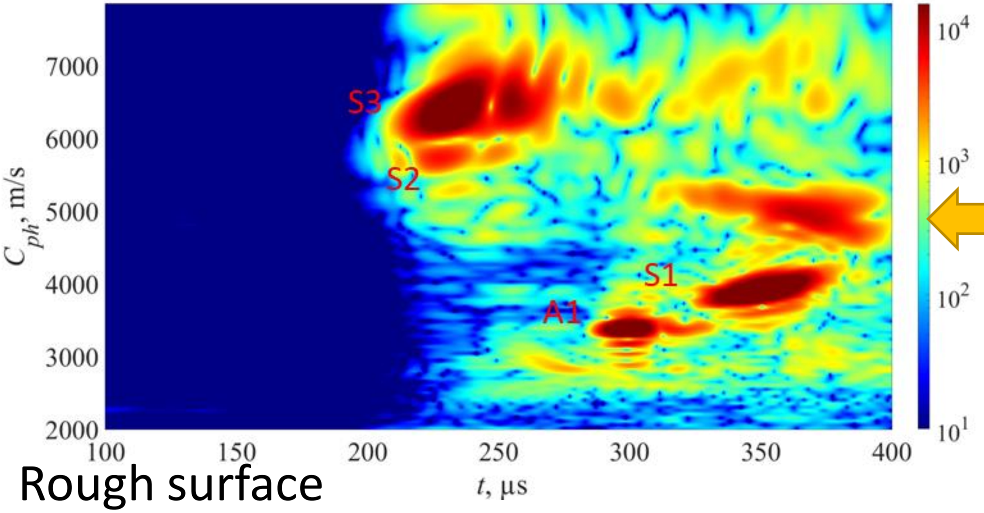


Adequacy of the model for the experiment

Experiments



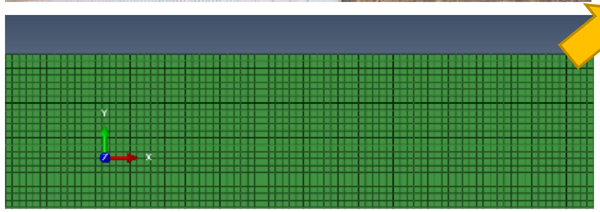
Flat surface

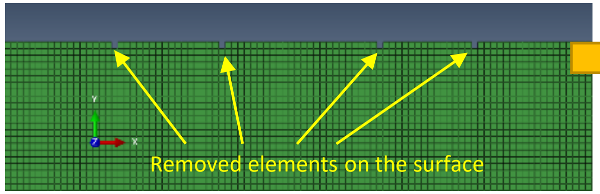


Rough surface

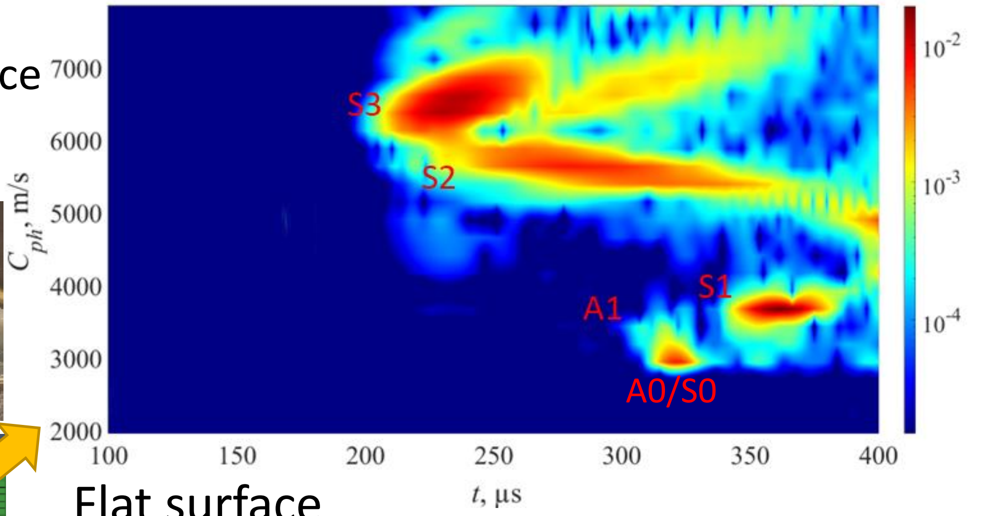
Performed experimental investigations:

- On a flat plate surface
- On a pipe with a rough surface
- Modeling was conducted

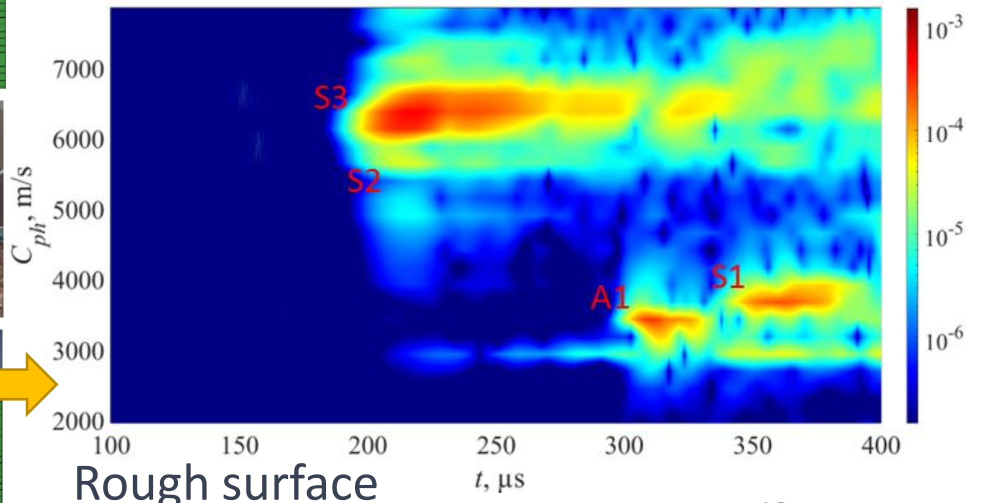




FEM models



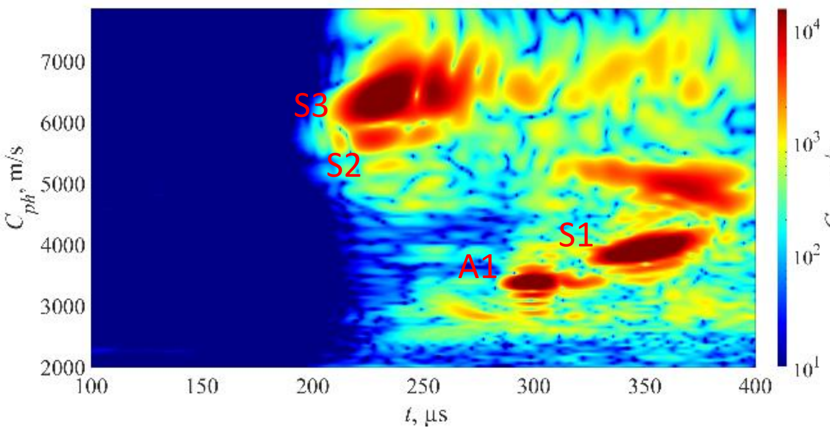
Flat surface



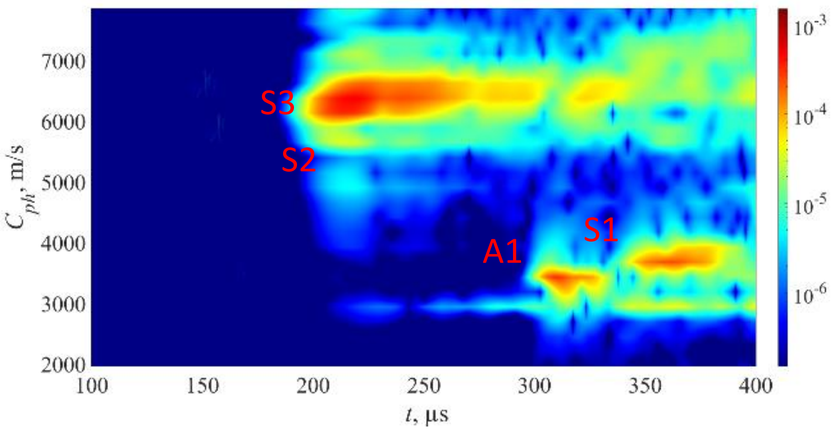
Rough surface

The influence of water filling

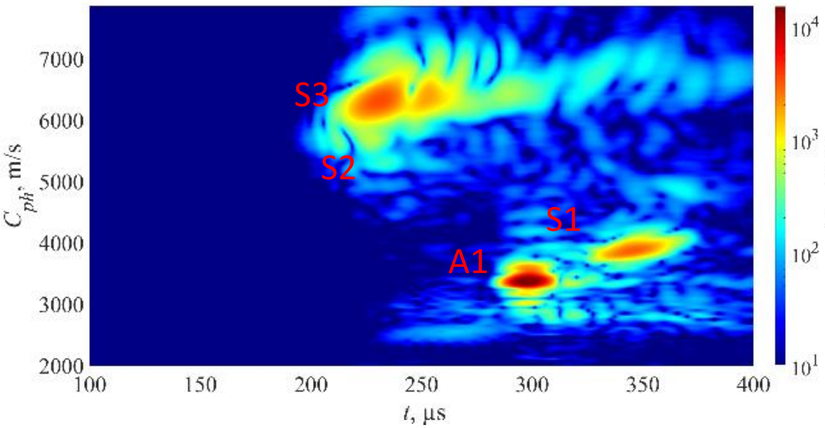
Dry specimen



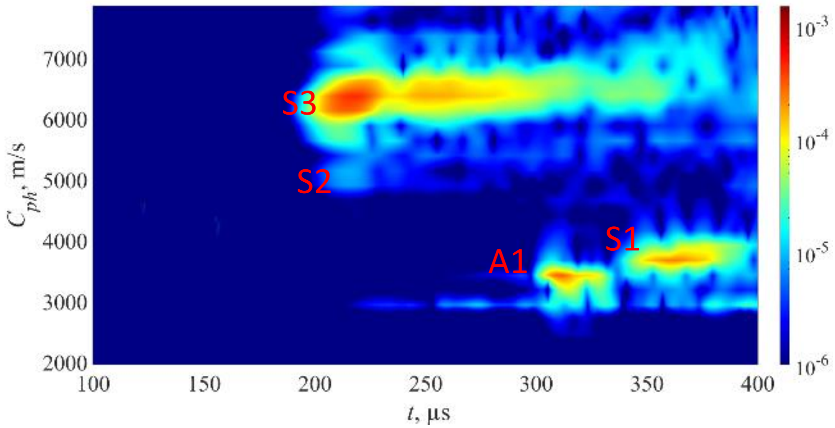
Dry FEM



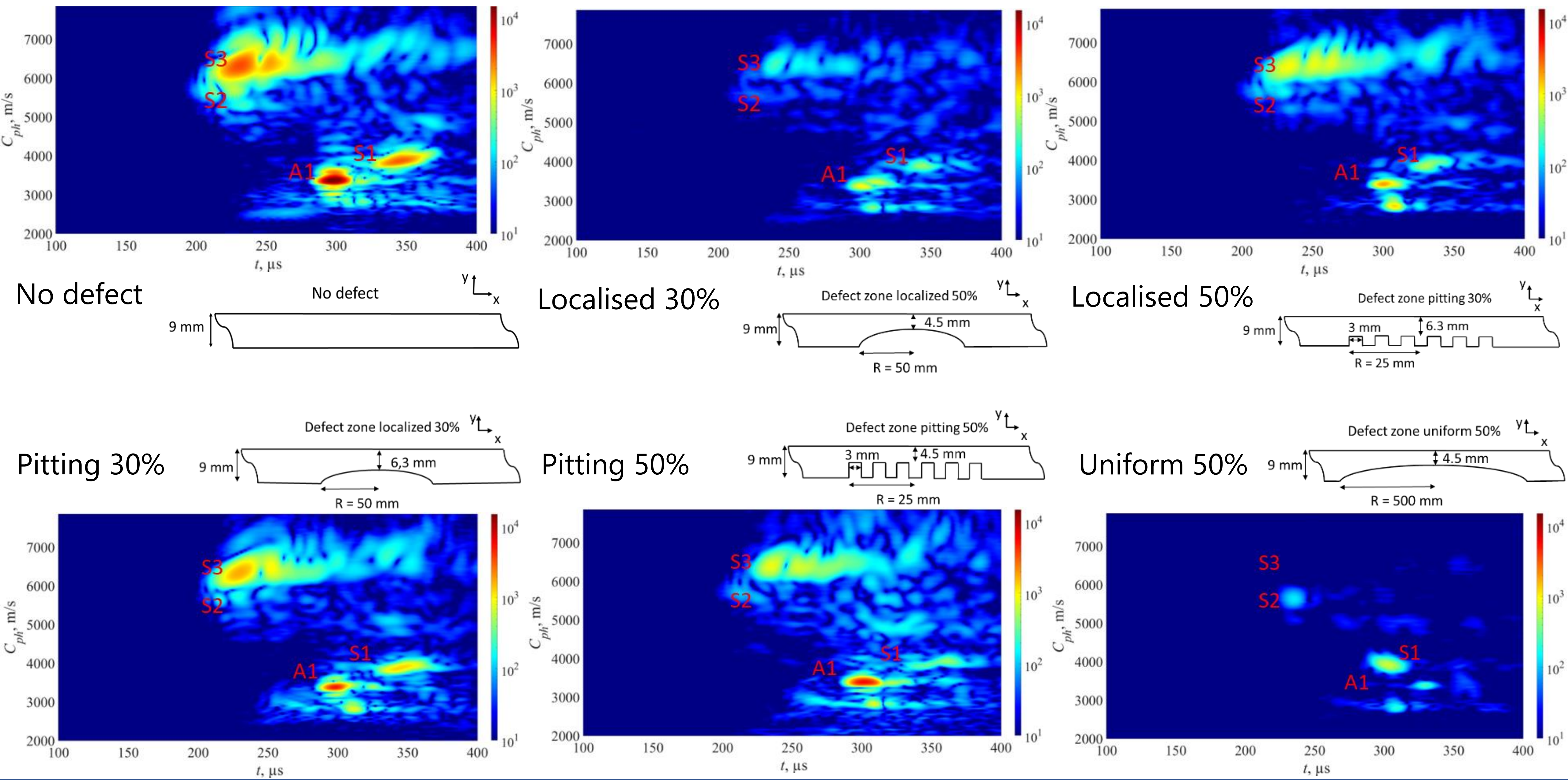
Filled pipe



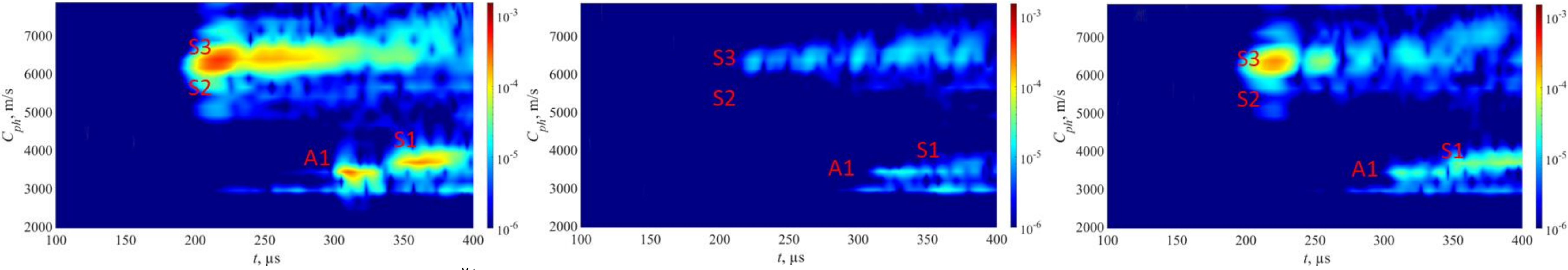
Filled FEM



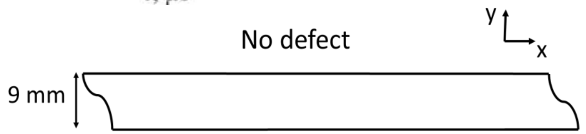
Analysis of the influence of defects on the generated modes in the experiment



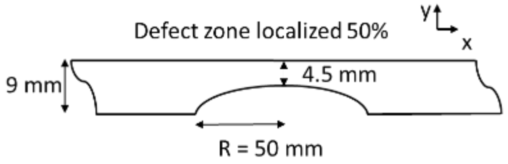
Analysis of the influence of defects on the generated modes in the Finite Element Method (FEM)



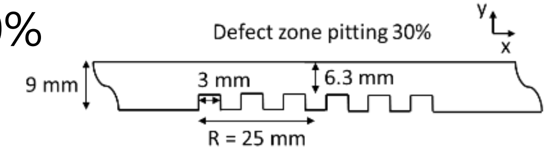
No defect



Localised 30%

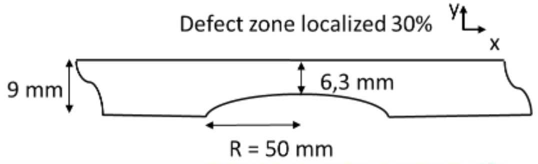


Localised 50%

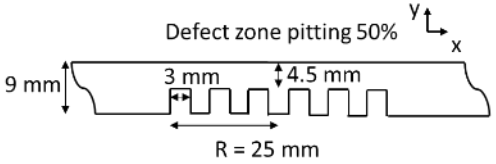


Not only demonstrates simmilarities, FEM data can also be used for training a neural network.

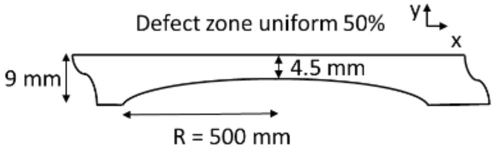
Pitting 30%

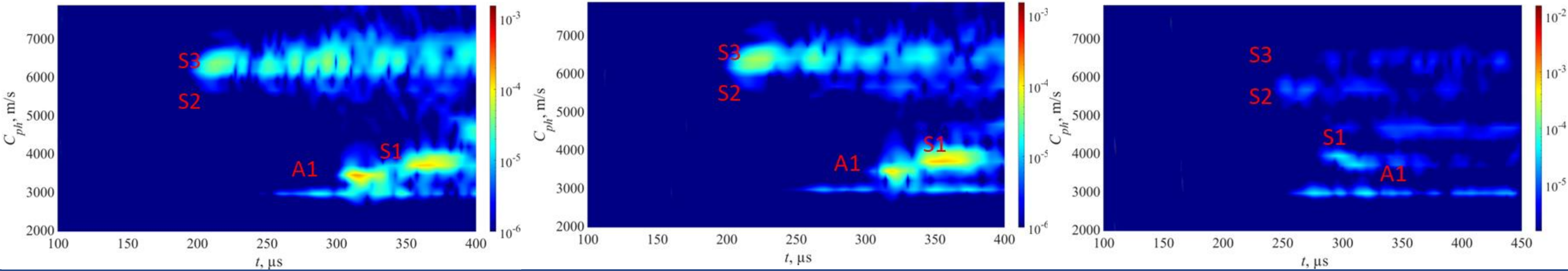


Pitting 50%

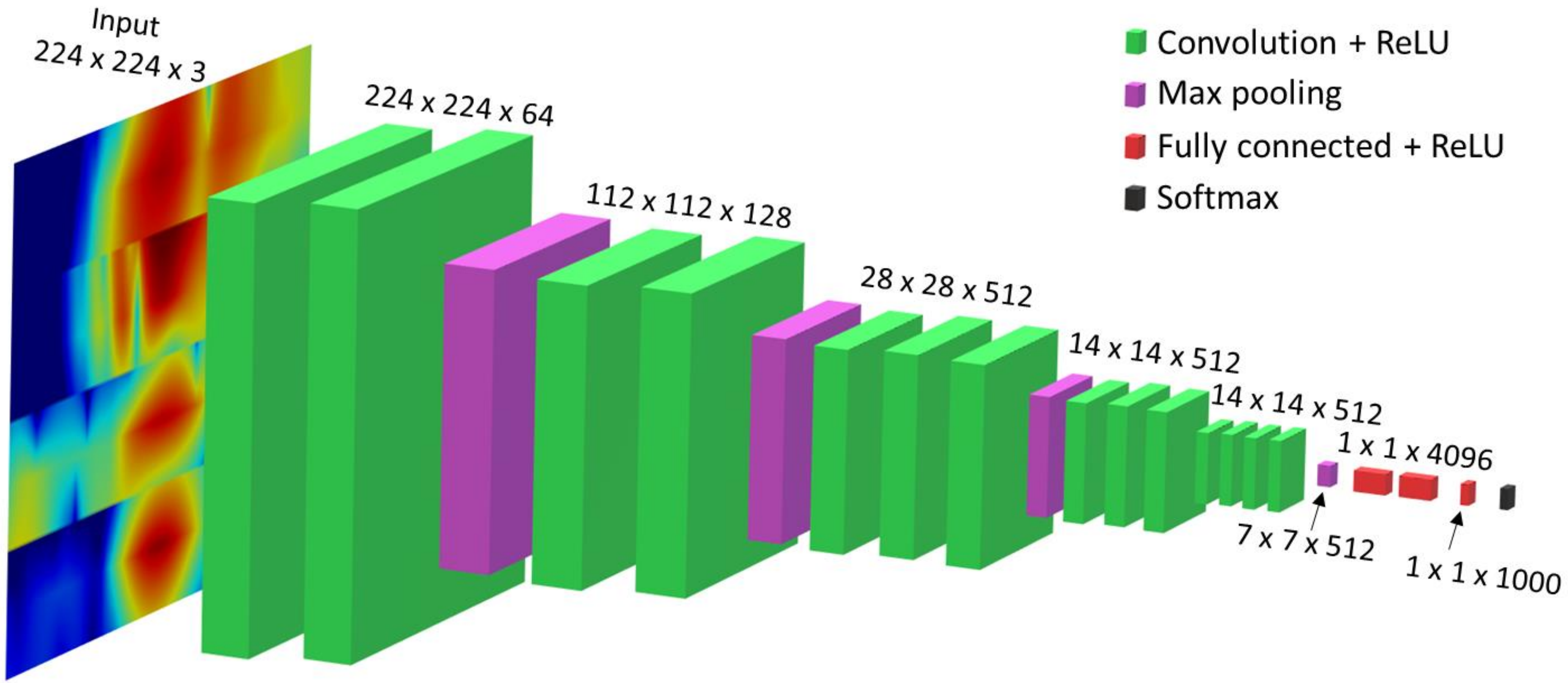


Uniform 50%



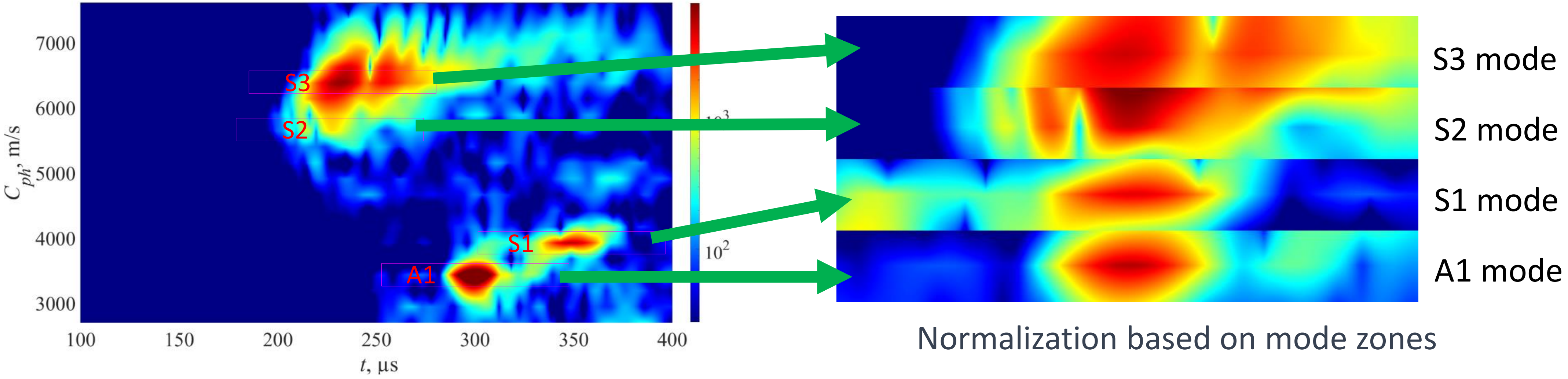


VGG-16 architecture



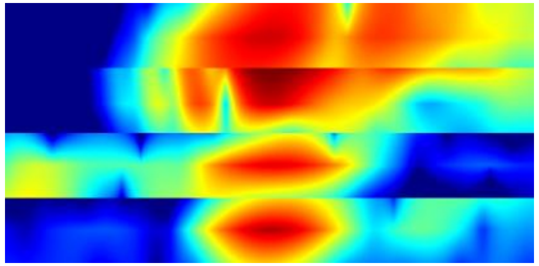
VGG-16 is a convolutional neural network consisting of 16 layers, including 13 convolutional layers and 3 fully connected layers. It is designed for tasks such as image training and classification.

Data segmentation for a neural network

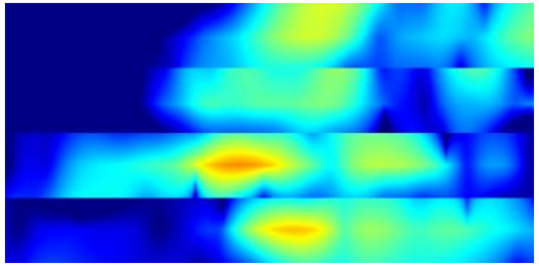


Normalization based on mode zones

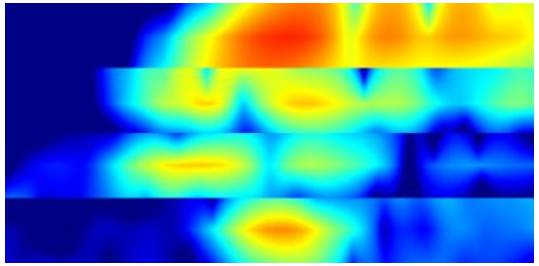
No defect



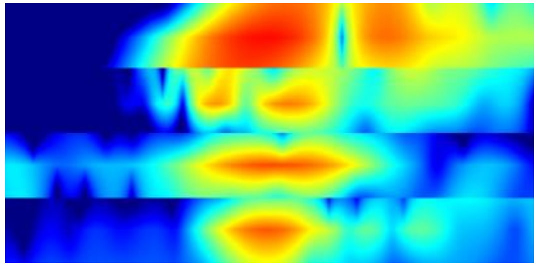
Localised 30%



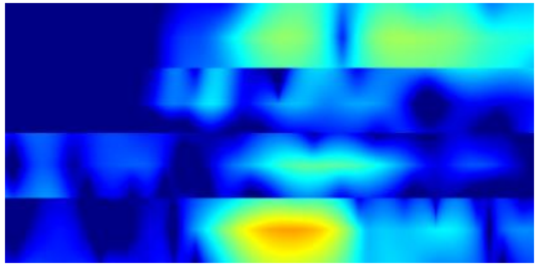
Localised 50%



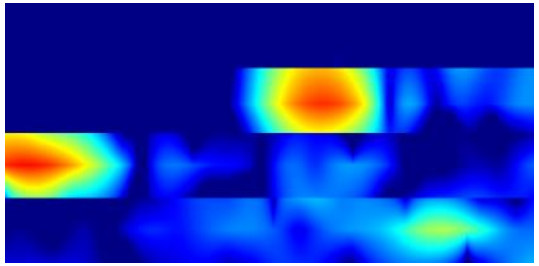
Pitting 30%



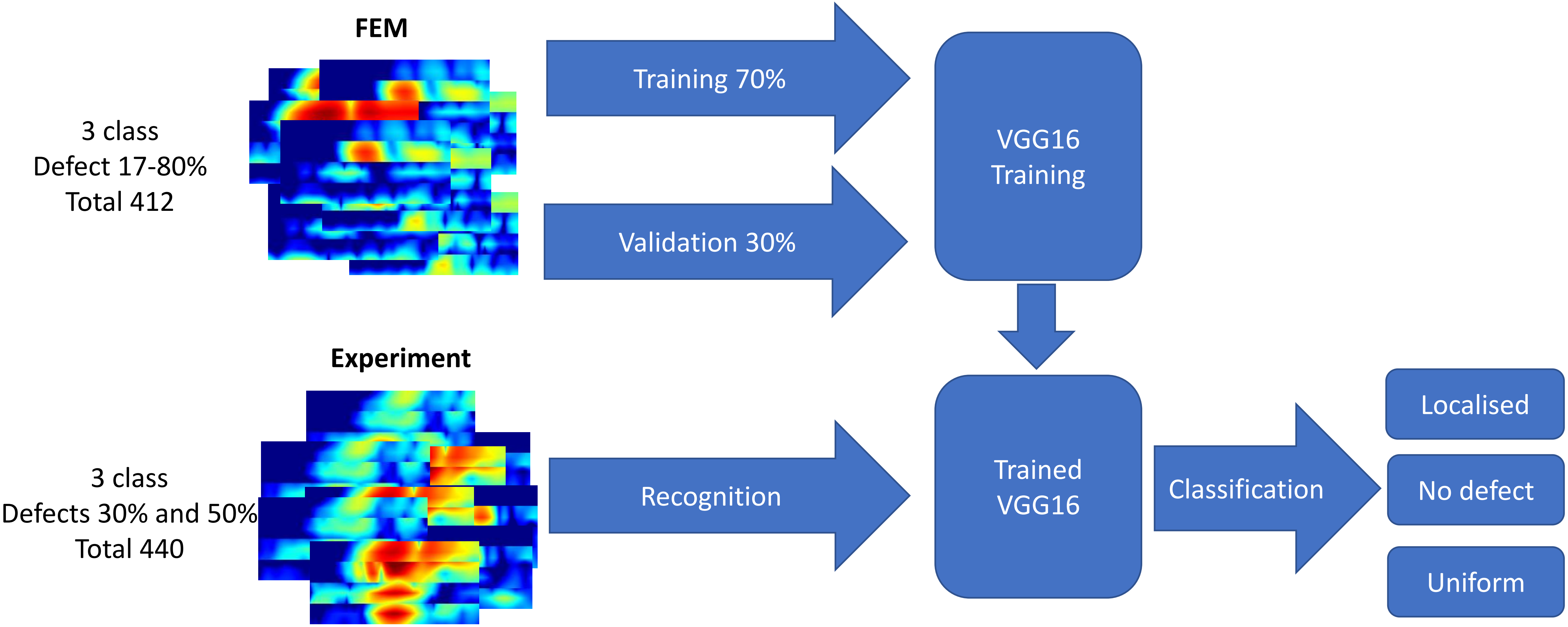
Pitting 50%



Uniform 50%

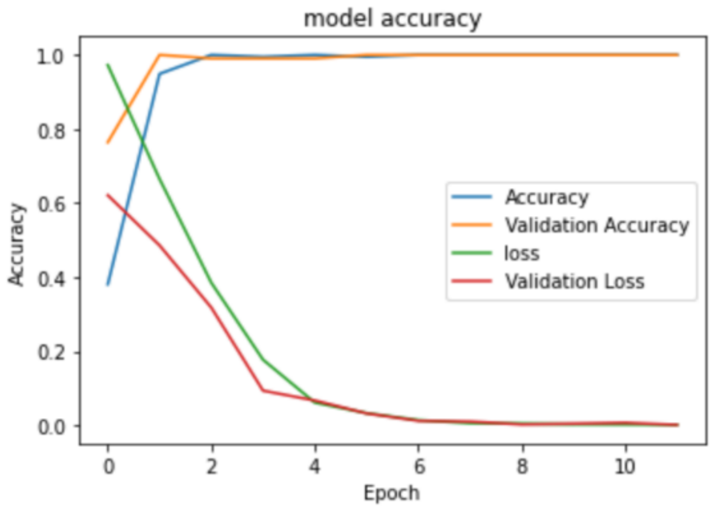


Training a neural network with Finite Element Method (FEM) data and recognition of experimental data

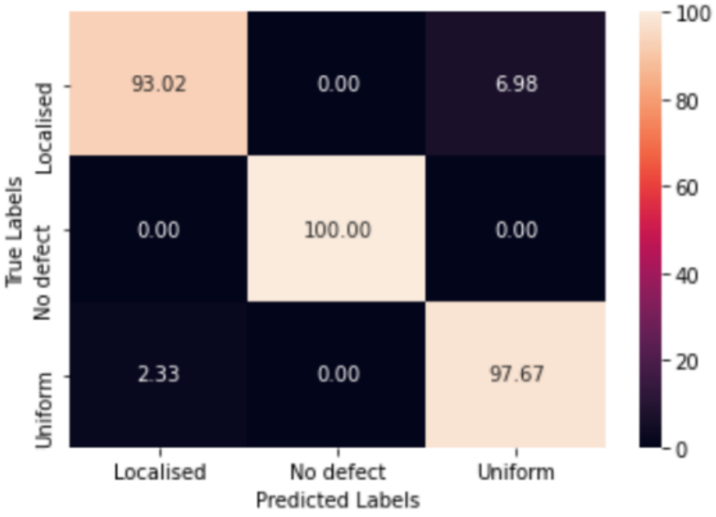


Model efficiency when trained with Finite Element Method (FEM) data using 17-80% depth defects

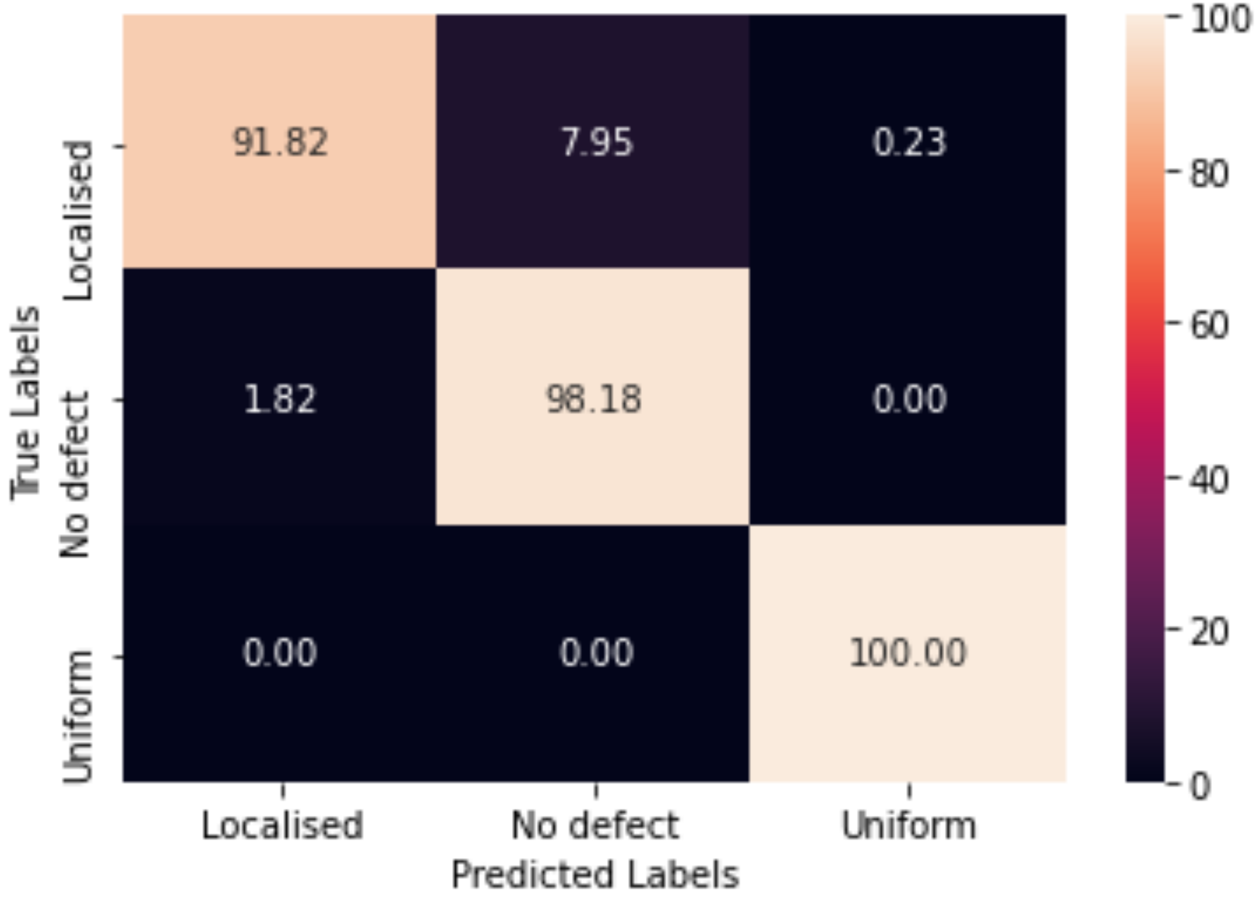
Machine learning curve



FEM 30% validation matrix



Experimental data classication matrix



Conclusions

- Using numerical modeling methods, higher-order guided wave modes propagating in the wall of steel pipe were investigated to determine their parameters influencing excitation capabilities, propagation losses, and potential interaction with corrosion damage.
- Selective excitation method for higher-order modes was developed and tested using the finite element method. Key factors and parameters influencing the excitation were identified through experimentation, which involved exciting S3, S2, S1, and A1 modes in plate and cylindrical structures.
- Method was proposed for the excitation and reception of higher-order modes in pipe structures, accompanied by a data visualization and analysis approach based on mode phasing in a pitch-catch configuration. This facilitated the identification of changes in wave propagation parameters caused by corrosion damage, enabling the detection and identification of defects.
- Specially designed specimen with simulated corrosion defects and a corresponding numerical model were utilized to validate the proposed method. Through experimental and numerical studies, the detection capabilities of corrosion defects using higher-order modes were confirmed, supporting the effectiveness of the proposed approach.
- Artificial neural network were suggested for the analysis of multimodal data and for the detection and identification of corrosion defects. The network were trained using data from the numerical model, encompassing defect depths ranging from 17% to 80% of the wall thickness. The trained network successfully detected and classified defects in the experimental data. The results showed that 92% of localized-type defects, 100% of uniform defects, and 98% of non-defective cases were correctly identified.

Thank you for your attention
Questions?

This research was funded by the Research Foundation of the Research Council of Lithuania under the project POLITE "Assessment of the distributed and concentrated pipeline corrosion by means of ultrasonic testing and machine learning methods", No. MIP2113.