Reliability Assessment of Guided Waved-based Structural Health Monitoring system in pipe application

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Introduction

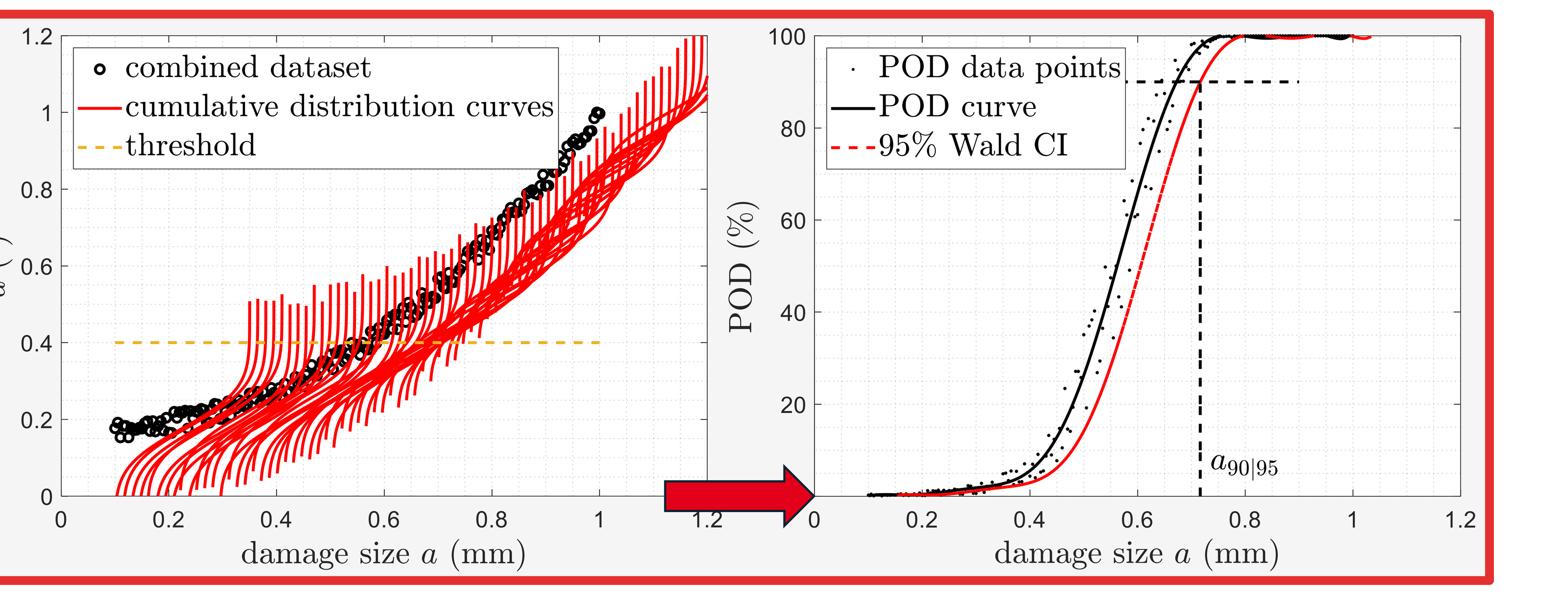
Guided Wave-based Structural Health Monitoring (GWSHM) systems are used to monitor and assess the integrity of structures like pipelines, power plants, and aircraft permanently and non-destructively by permanently mounting transducers and evaluating its automated recorded measurement. Even though having such systems increases the level of safety in life, the reliability assessment of GWSHM systems is a vital burden that prevents them from being widely deployed in more industrial applications because there is no clear guideline. The model-assisted Probability of Detection (MAPOD) technique emerges as a promising approach that enables the generation of a statistically independent dataset by utilizing a simulation model. Its data is used as input for classical POD analysis as described in MIL-HDBK-1823. But although simulation tools are highly effective in accounting for and simulating structural uncertainties, they fall short in modelling system, operational and environmental uncertainties. Consequently, the resulting POD analysis remains simulation-based, lacking seamless integration with reality. Additionally, classical POD analysis is confined by specific guidelines mandating a linear relationship between damage size and its corresponding damage indicator for applicability.

In order to generate a more realistic POD analysis, this poster presents the hybrid POD approach as developed in the GW4SHM project [1], published in [2,3]. I combines simulated damage scenarios, including structural uncertainties, with experimental data, taken from a real GWSHM system at the pristine stage and under the influence of environmental and system uncertainties.

Hybrid POD - Methodology

The aim of the novel hybrid POD approach is to enable system specific information about the systems reliability and sensitivity. This is done by using experimental data of the specific system in the undamaged state and combining it with simulation data of the damaged state. The following steps represent key aspects of the method:

1. From the experimental campaign at pristine state, the dataset should be normally distributed.
2. Model defect states using simulation tools.
3. Utilize the mean value of the experimental normal distribution curve to compensate for the error between the simulated model and experimental setup, resulting in a combined dataset.
4. Treat each data point of the combined dataset as a cumulative distribution function, with its mean equivalent to its point value and its standard deviation equivalent to the standard deviation of the experimental damage indicator.
5. Once the threshold is set, identify the POD data points as the intersection between each cumulative distribution function and the threshold. Then, polynomial regression is used to fit the POD curve, and the Wald confidence interval is utilized to calculate the 95% confidence interval.

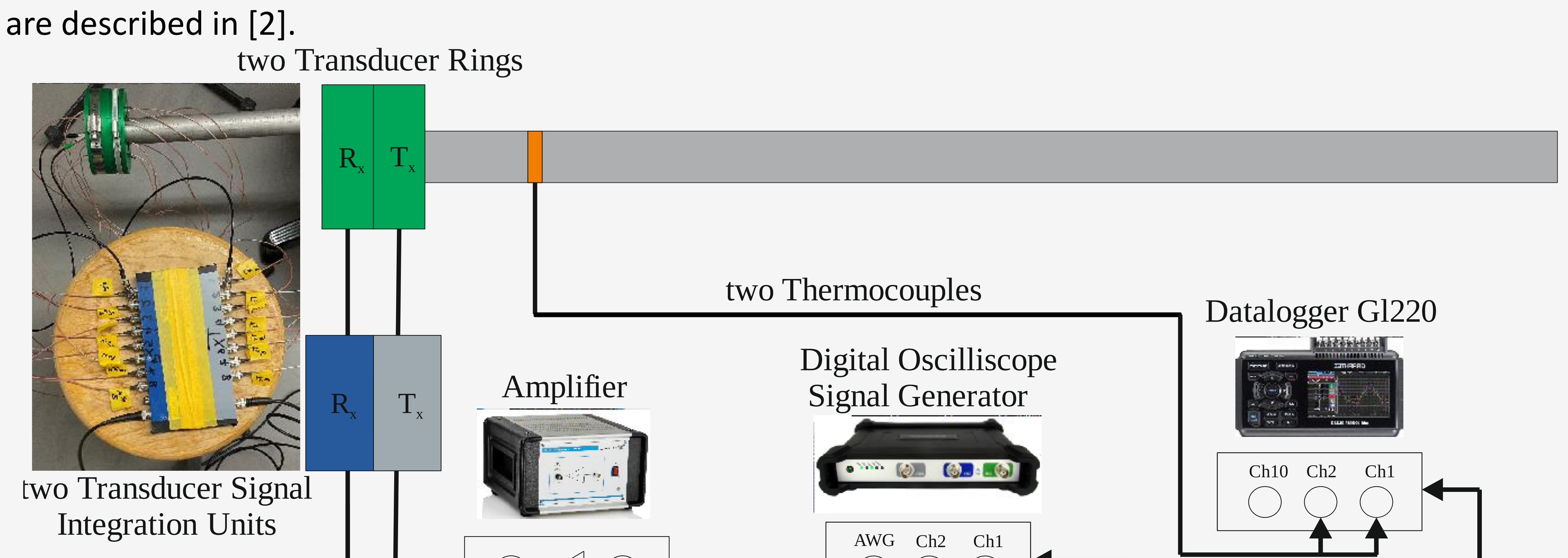


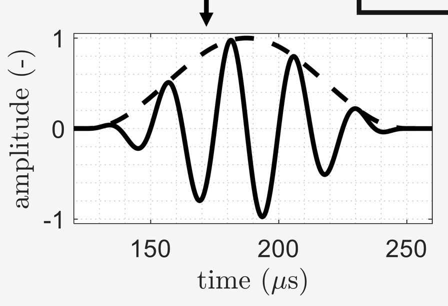
Experimental setup

This approach is demonstrated on a steel pipe with a GWSHM system employing:

- Two arrays of PZT shear elements bonded around the circumference of the pipe; one to excite the fundamental pure torsional mode, T(0,1), and another to receive the echo.
- Two thermocouples to record the temperature.

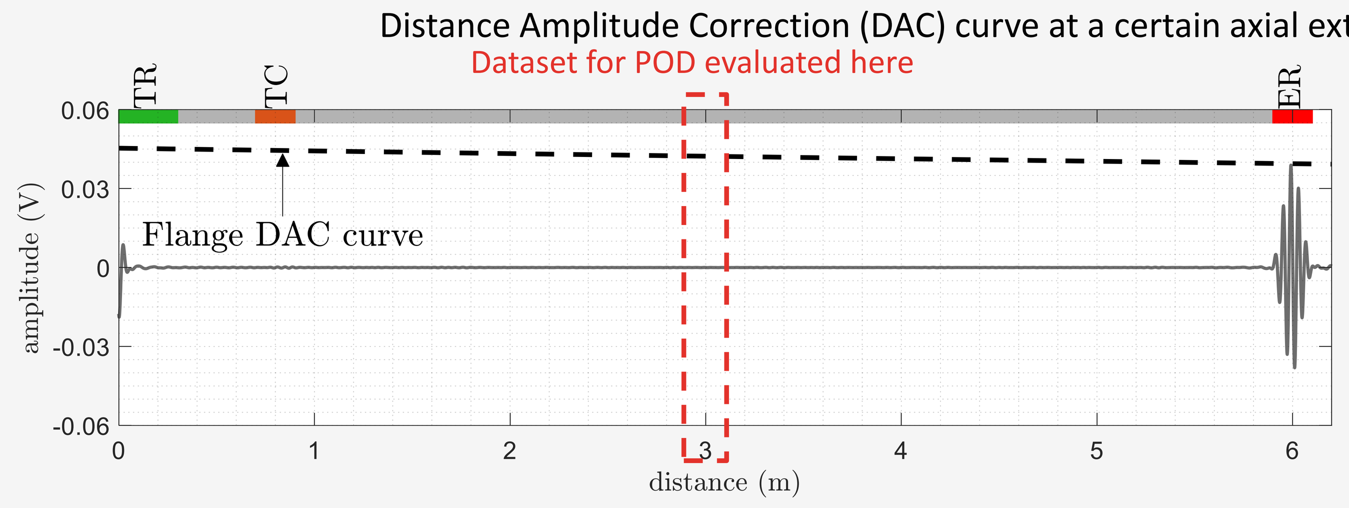
The excited signal is a five- cycle toneburst signal with central frequency of 40kHz. The details of this setup are described in [2].





Signal Processing:
In total, 550 measurements were recorded in the pristine state with temperature varying between 10 – 20°C.

1. Bandpass filter between 25 and 55kHz.
2. Location Specific Temperature Compensation (LSTC) technique.
3. Finally, Reflection Coefficient (RC) damage indicator is applied in time domain as the amplitude ratio between the amplitude and the Flange Distance Amplitude Correction (DAC) curve at a certain axial extent.

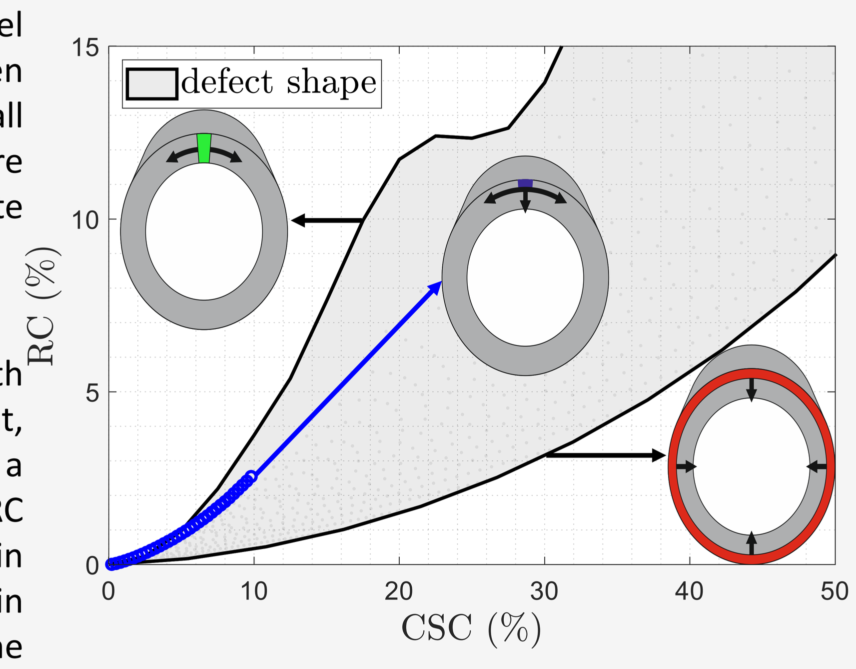


Once the RC damage indicator for POD analysis is applied, two statistical tests have been used:

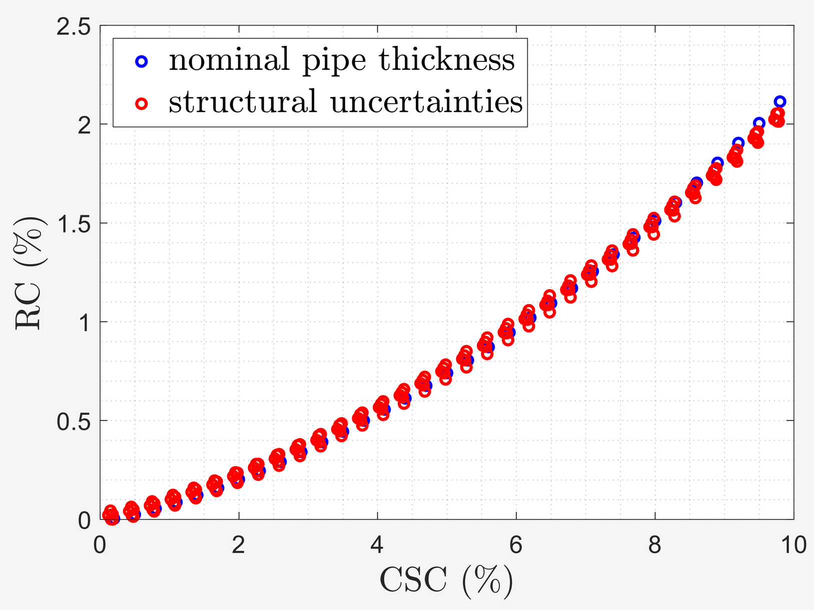
1. Anderson Darling null hypothesis tests verifies that the dataset is normally distributed.
2. Autocorrelation and Ljung-Box Q tests suggest that dataset is sufficiently uncorrelated.

Numerical simulations

3D numerical models have been generated to model 2D defects. The crack-like 2D defects have been modeled with different circumferential and wall defects, but zero axial extent. These models were generated and executed using the commercial Finite Element Method (FEM) software Pogo.



Signal Processing:
A total of 800 models have been generated with different damage growth patterns (see figure right, green and red are representing extremes, blue is a representative damage growth pattern). The RC damage indicator is then applied in the time domain as the ratio between the amplitude at a certain damage location and the maximum amplitude of the incident signal.



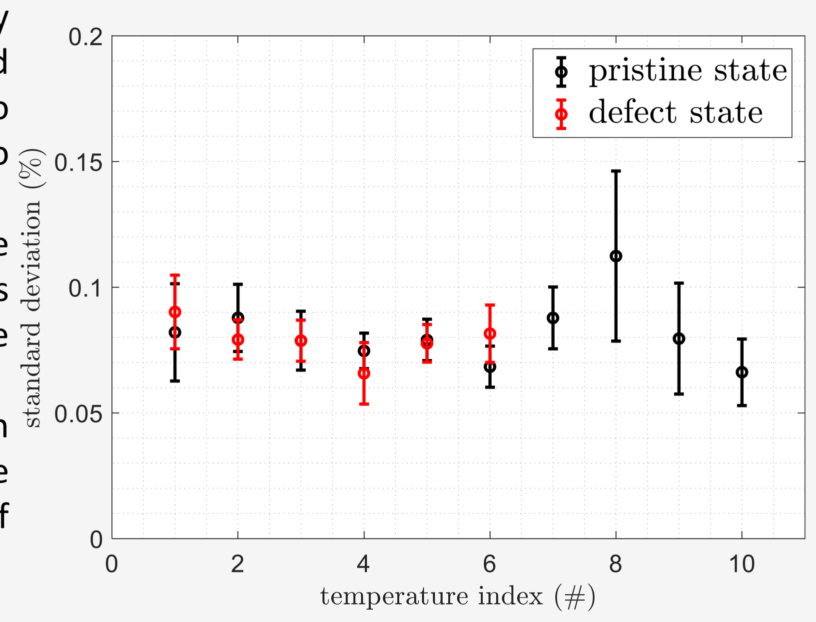
Adding Structure uncertainties:
According to ASME A312, the allowed tolerance in nominal pipe thickness is +20% and −12.5%. Therefore, seven configurations with different thicknesses were modelled (See figure left, red is representing the nominal pipe thickness, and blue represents the structural uncertainties modelled).

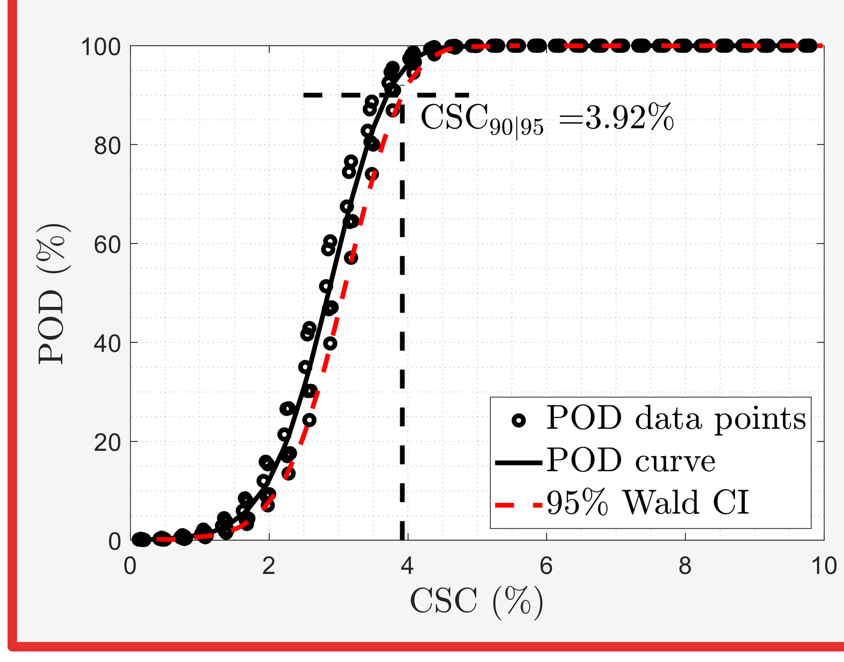
For the Hybrid POD analysis, the representative damage growth pattern (represented in blue) is used.

Results – Hybrid POD analysis

Validation of numerical model and necessary assumptions for the application of the novel Hybrid POD approach after introducing a five-state defect to the experimental campaign and modelling it, two main validations can be obtained:

1. The standard deviation of the RC damage indicator in the experimental dataset remains unchanged, regardless of the state of the structure.
2. There is good agreement between the simulation modelling of the introduced defect states and the experimental dataset, verifying the efficiency of the 3D model generated using Pogo software.





Hybrid POD analysis:

- The threshold is set as a noise level +6dB.
- The noise level is considered as twice the standard deviation of the RC damage indicator of the pristine state.
- Polynomial regression up till the 9th level is considered in fitting the POD curve.
- The smallest defect that can be detected with 90% probability and 95% Wald confidence interval is 3.92% CSC for the chosen damage growth pattern.

Conclusion

- The integration of damage scenarios with experimental baselines has been successfully demonstrated in this poster. The proposed approach leads to a realistic POD analysis.
- The novel method presented shows the possibility to generate POD analysis using a non-linear trend, while the POD analysis described in MIL-HDBK is restricted to linear trend between the DI vs. damage size.
- Statistical analysis shows that the temperature compensated data did not show serial correlation beyond that expected from random noise.
- The demonstrated hybrid POD approach, based on combining simulation with experiment, is one step towards a more realistic POD analysis. This approach has the ability to assess the reliability of the GWSHM system regardless of the trend of damage indicator vs. damage size. Finally, assessing the SHM pipe specific system's reliability based on representative pristine data only is possible.

Publication

[1] GW4SHM. https://www.bam.de/GW4SHM/EN/Navigation/Home/home.html.
[2] Bayoumi, A., Vogt, T., and Mueller, I., 2023. New approach for reliability assessment of guided wave-based structure health monitoring system on a pipe application. In 8th International Workshop on Reliability of NDT/NDE, vol. 12491. SPIE.
[3] Memmolo, V., Moll, J., Schackmann, O., Freitag, S., Volovikova, A., Tschöke, K., Savli, E., Lugovtsova, Y., Moix-Bonet, M., Bayoumi, A., and Mueller, I., 2023. Promoting Novel Strategies for the Reliability Assessment of Guided Wave Based SHM Systems. Structural Health Monitoring 2023.

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