



Guided wave ultrasonic feature determination in Type IV composite overwrapped pressure vessels towards the digital twin

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Abstract

The digitalization of quality control processes and the underlying data infrastructures for safety relevant components, such as hydrogen pressure vessels, plays a significant role in the transition towards Industry 4.0. In the current safety regulations for hydrogen pressure vessels, there is no established concept for structural health monitoring. The development of a reliable structural health monitoring methodology for monitoring the structural integrity of pressure vessels enables a fast-forward transition from personnel- and cost-intensive recurring inspections, a.k.a. periodic maintenance, to predictive maintenance.

In the work presented; we investigated the application of ultrasonic guided wave propagation to monitor and assess the condition of Type IV composite overwrapped pressure vessel (COPV). A sensor network of fifteen piezo-electric wafers is placed on the carbon fibre reinforced composite cylinder. Five different artificial damage configurations are created by gluing two different weight blocks on three different locations. The database containing measured guided wave data sets is enriched by two different boundary conditions. We utilized an open-source software, openBIS lab-notebook, to store and analyse experimental datasets. The guided wave ultrasonic signals were investigated and analysed by using commonly used ultrasonic features (e.g., amplitude, frequency, time of flight) as well as non-traditional time-series features (kurtosis, skewness, variance). The features were used to calculate damage index and the detection performance for the results has been evaluated. The results suggest that both traditional and non-traditional features assume significant importance in artificial damage detection. The future works will additionally involve the impacts of operational conditions, such as periodic pressure variations temperature loadings as well as material degradations.

KEYWORDS: Industry 4.0; Composite overwrapped pressure vessels; structural health monitoring; ultrasonic guided waves; predictive maintenance



1. Introduction

The transition to Industry 4.0 and NDT 4.0, is a natural consequence of developed digitalization technologies that goes side-by-side with structural health monitoring (SHM). SHM enables us to collect data continuously to determine the actual status of the components. SHM technologies open the possibility to significantly reduce the cost-intensive periodic inspections, to replace them with predictive maintenance, and even to calculate remaining useful lifetime of structures. SHM systems are attractive to industries like aerospace and energy, however, the applications are limited due to the lack of regulations.

Hydrogen pressure vessels, as a possible application, are very important for the future of the energy industry. There are five types of pressure vessels: all-metal (I), metal lined with looped composite around cylindrical part (II), metal-lined and fully overwrapped composite (III), plastic lined with fully overwrapped composite (IV) and fully composite (V) [1]. The current inspection methodologies like conventional hydraulic testing are designed for metal pressure vessels and they do not seem to provide reliable information about the status of the composite vessels [2]. In addition, due to the different failure mechanisms of composites, these tests might cause propagation of small and undetected damages. Alternatively, an SHM system that can be built for composite vessels will not only ensure safety and extend lifetime but also might eliminate unnecessary inspections [3].

In the field of SHM, there are numerous works investigating the structural integrity of cylindrical structures with ultrasonic guided waves due to their ability to propagate long distances. Li et.al. studied three different types of guided wave modes (torsional, longitudinal, and flexural) and showed that selection of excitation frequency is very important when studying metal pressure vessels [4]. Although the attraction in application of composite pressure vessels is increased due to their advantages such as low-weight and increased lifetime, the utilization of guided wave modes and the verification process required is more complicated than for all-metal Type I vessels [5].

In this work, SHM using ultrasonic guided waves was implemented on a Type IV composite overwrapped pressure vessel (COPV). Guided waves travelling through the pressure vessel were excited and recorded by a sensor network of fifteen piezoelectric sensors. Artificial damages are represented by attaching weighted blocks to several locations on the cylinder. The recorded signals were analysed using tomographic data fusion over the cylindrical part of the vessel. Time, frequency, amplitude, and statistical features were used as damage indicators. The results were evaluated by calculating the area under the receiver operating characteristics curve.

2. Methodology

2.1 Structure under investigation

The structure under investigation was a fully composite type IV hydrogen high pressure vessel (COPV) that was manufactured by NPROXX. The vessel had a plastic liner with 2 mm wall thickness and overwrapped carbon fibre reinforced polymer composite with

15.66 mm wall thickness. The length of the cylinder from valve to valve was 1510 mm, the cylindrical part was 1270 mm, and the outer diameter was 228 mm.

2.2 Structural health monitoring with guided waves

For monitoring the condition of Type IV COPV a sensor network of piezoelectric wafers (PZT) was applied on the cylindrical surface. The sensor network consisted of three rings each having five PZTs, mounted considering optimized network design with maximum coverage [6]. The spacing between the PZTs around the circumference was approximately 72 degrees, and 610 mm is kept between the rings (Figure 2 (a)). DuraAct patch transducers (P-876K025) with a 10 mm circular ceramic embedded in a ductile polymer from PI Ceramics (Lederhose, Germany) were used as sensors. The PZTs were bonded to the COPV's surface with a thin layer of two-component epoxy adhesive and then wired to Vantage 64 LF system from Verasonics (Kirkland, USA).

To evaluate the robustness of the methodology, several types of variations were considered (Table 1). In essence, five different artificial damage scenarios (D1 - D5) were investigated where weighted blocks as artificial damages were placed in various parts of the vessel (Figure 2 (b)). D4 was a combination of D2 and D3, and D5 was a combination of D1 + D3. The combination of experimental set-up variations is described in Table 1.

Table 1. Description of variations considered during data acquisition.

Types of variations	Description
Damage scenarios	D1) Between S1 and S6, 20 cm away from S1 D2) Between S6 and S10, 30 cm away from S6 D3) Between S1, S6 and S7, 40 cm and 36 degrees from S1 D4) Combination of D2 and D3 D5) Combination of D1 and D3
Damage sizes	DS1) Metal block weighting 513 g, 3 cm diameter DS2) Metal block weighting 330 g, 3cm diameter
Boundary conditions	BC1) COPV on fixed castors, support on four points BC2) COPV assumed laid free, nozzles on the frame
Excitation frequencies	F1) 130 kHz F2) 220 kHz

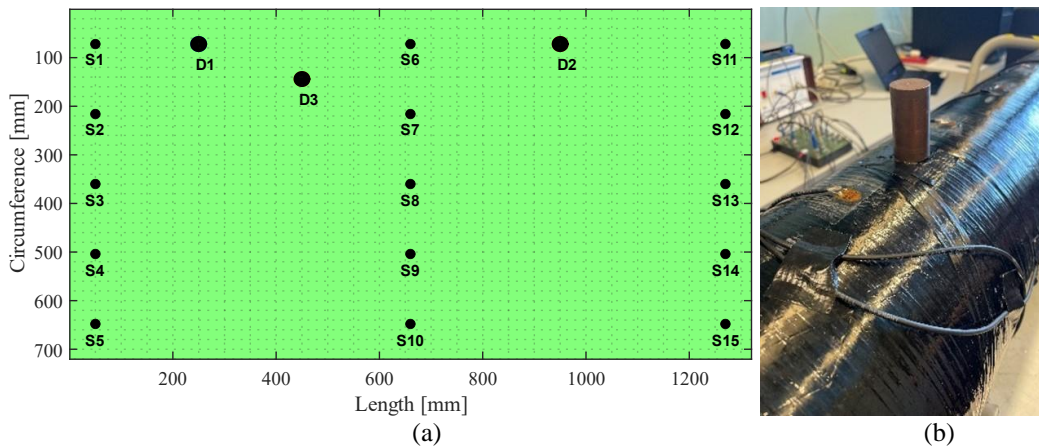


Figure 1. (a) Unwrapped cylindrical surface of COPV with the sensor positions 1-15 and the artificial damage locations D1-D3. (b) Photograph of a metal block used as artificial damage.

2.3 Data infrastructure

The experimental database has been built under open-source-software openBIS. The data is stored with FAIR principles, all the modifications have been prevented [7]. The data format has been selected as *hdf5* file format where both sensor recordings and metadata are stored. Each *hdf5* file consists of the pitch/catch signals, sampling frequency, channels, timestamps, and other related metadata.

2.4 Post-processing for data fusion

The cylindrical area of the vessel is considered for the tomographic data fusion. The recorded signals are processed based on reconstruction algorithm for probabilistic inspection of damage (RAPID) [8]. A grid representing the surface structure is defined with 1 mm distance.

2.5 Damage index

The damage index (DI) is usually referred to the calculated difference between the pristine and the damage introduced state. In this work, fifteen different damage indices are evaluated based on time and frequency responses as well as shape characteristics (Table 2).

Table 2. Damage indices based on feature extraction

DI		DI		DI	
CC	Cross correlation	SSSD	Signal sum of squared differences	CCMPD	Cross-correlation maximum percentage difference
CCTOF	Cross-correlation-based TOF difference	HTOF	Hilbert transform-based TOF percentage difference	SAHM	Signal amplitude Hilbert transform maximum
FAMAX	Frequency domain maximum amplitude	FAUC	Area under frequency spectrum	ARRFD	Parametric resonance frequency differences
F-SKEW	Skewness of frequency domain response	F-KURT	Kurtosis of frequency domain response	F-VAR	Variance of frequency domain response
SKEW	Skewness	KURT	Kurtosis	VAR	Variance

2.6 Evaluation method

The resulted fusion images are evaluated considering the placement of artificial damage locations and the receiver operating characteristics (ROC). The figures are evaluated by binarization based on 300 threshold points. Then ROC curves were obtained by plotting true positive ratio to false positive ratio. The area under the ROC curves was considered as the defect detection and localization performance for each damage indicator and each artificial defect case.

3. Results

RAPID results for the unwrapped cylinder in selected damage combinations are given in Figure 3 and Figure 4. The higher values represent the defect likelihood, and the blue circle indicates the real position of the artificial damage.

The evaluation results for the three best performing damage indicators (CCMPD, FAUC, and VARIANCE) and eight damage variations are shown in Figure 5. The variations for excitation frequency are given with colour variance (blue/light blue 130 kHz, red/light red 220 kHz). The different scatter plot markers represent the changes in the boundary condition.

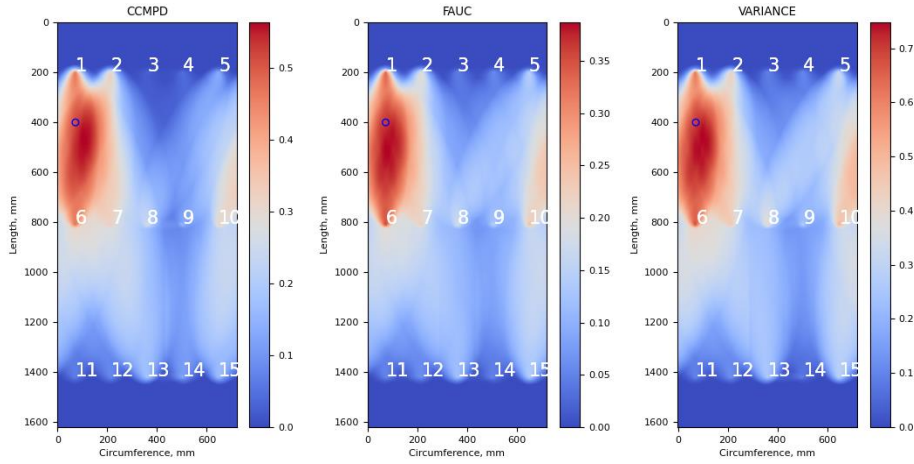


Figure 3. Fusion results for the case D1_DS1_BC2_F2 of the best damage indicators.

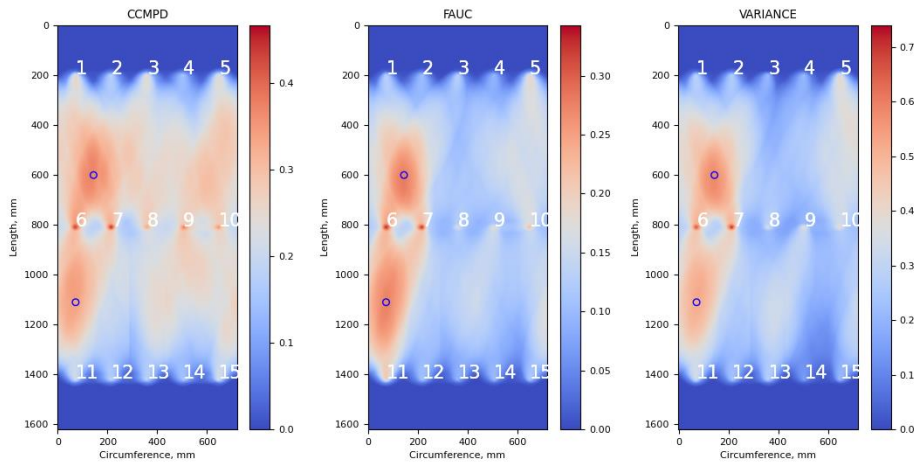


Figure 4. Fusion results for the case D4_DS3_BC1_F1 of the best damage indicators.

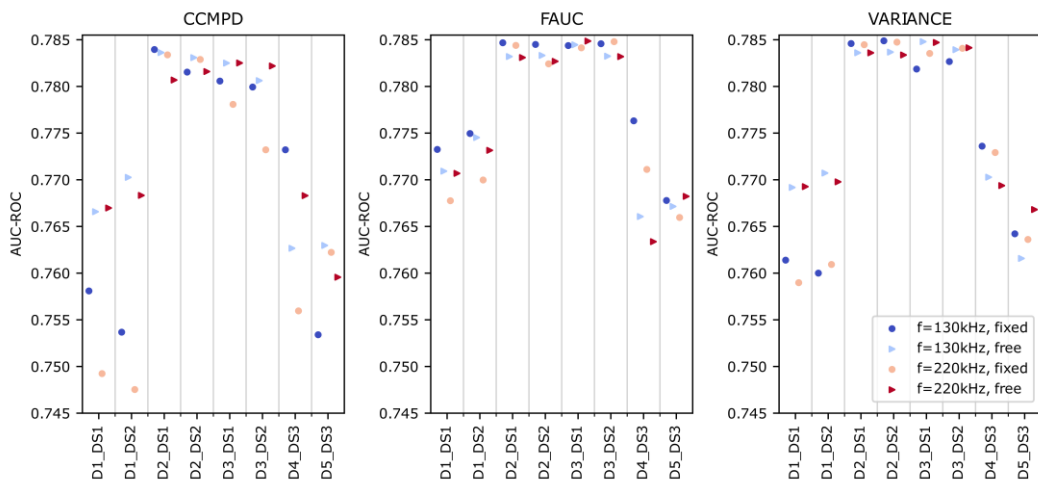


Figure 5. Detection performance of best damage indicators based on area under ROC curve.

4. Conclusions

The results show that some damage indices are more sensitive than others to the changes through damage size, damage location, boundary conditions and excitation frequency. The damage detection and damage localization for the artificial damages that created by gluing weight blocks are best when damage indices are chosen as variance, cross correlation density ratio, or area under frequency spectrum. While this study analyses the characteristic features that can be mapped in future works, it should be noted that other damages – specifically the real defects such as delamination breakage – can perform differently with the proposed techniques.

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