Ultrasonic Guided Wave Based Intelligent Structural Health Monitoring of Pressure Vessels

SHIRSENDU SIKDAR, AHMED HUSSAIN ALI ABDELRAHMAN, MOSBEH R. KALOOP and MOHAMED M. AWAD

ABSTRACT

Pressure vessels are critical components in industries such as hydrogen energy, cryogenics, and oil and gas, where they are subjected to harsh environmental and operational conditions. Corrosion remains a predominant challenge, gradually degrading structural integrity and increasing the risk of catastrophic failures. Conventional inspection techniques, such as visual assessments and periodic ultrasonic testing, often lack real-time monitoring capabilities, leading to delayed damage detection and unplanned maintenance. To address these limitations, this study explores the application of ultrasonic guided waves for autonomous structural health monitoring of pressure vessels. The research systematically examines the propagation characteristics of guided waves in stainless steel pressure vessels, focusing on their interaction with corrosion-induced defects. Through controlled experimental investigations, mode-specific amplitude variations are analyzed to establish their sensitivity to localized damage. Additionally, the study evaluates how internal pressure fluctuations influence guided wave behavior, providing insights into the dynamic response of the vessel structure under operational loads. By integrating guided wave analysis with an autonomous monitoring framework, the proposed approach enhances the early detection of corrosion damage, enabling predictive maintenance strategies. The findings contribute to the development of intelligent condition-based monitoring systems capable of real-time structural assessment, improving the safety, efficiency, and longevity of pressure vessels in demanding industrial environments.

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1. INTRODUCTION

Pressure vessels serve as indispensable components across numerous industrial domains, including hydrogen energy systems, chemical processing, cryogenics, and oil and gas transport. These structures are often subjected to high internal pressures, extreme temperatures, and corrosive environments, making their structural integrity a critical safety concern [1–3]. The failure of such systems can result in catastrophic consequences, including operational downtime, environmental hazards, and threats to human safety [4,5]. Corrosion, particularly localized and pitting corrosion, remains one of the most insidious degradation mechanisms affecting pressure vessels [6]. Traditional non-destructive testing (NDT) techniques—such as radiography, magnetic particle inspection, and conventional pulse-echo ultrasonic testing—are frequently employed to detect such flaws [7]. However, these methods are generally periodic, labour-intensive, and limited in their ability to provide continuous, real-time structural assessment [8,9]. As a result, damage can progress undetected between inspections, increasing the risk of sudden failures.

To overcome these challenges, structural health monitoring (SHM) techniques have garnered significant interest, aiming to provide continuous evaluation of structural condition and support condition-based maintenance strategies [10,11]. Among various SHM approaches, ultrasonic guided waves have emerged as a particularly promising tool due to their ability to propagate over long distances and interact sensitively with a wide range of damage types [12–14]. These waves, including Lamb and shear horizontal (SH) modes, exhibit dispersive and mode-dependent characteristics that make them suitable for monitoring complex geometries such as cylindrical vessels [15,16]. Recent advances in guided wave based SHM have demonstrated successful applications in pipeline monitoring, aircraft structures, and composite materials [17–19]. However, the specific behavior of guided waves in thick-walled, curved pressure vessels—especially under varying internal pressures and in the presence of corrosion-induced defects—remains underexplored [20,21]. Factors such as wave mode selection, frequency tuning, and multi-mode interactions add to the complexity of signal interpretation in such geometries [22,23]. In parallel, the integration of smart sensing systems, data-driven analytics, and autonomous monitoring frameworks is transforming traditional NDT into intelligent SHM paradigms [24–26]. Machine learning algorithms, when trained on guided wave features, have shown promise in improving defect classification, localization, and damage quantification accuracy [27–29]. Nevertheless, effective deployment of such systems in industrial settings still requires rigorous experimental validation, particularly under simulated operational loads that replicate realistic pressure variations and corrosion growth scenarios [30,31].

This study investigates the propagation characteristics of ultrasonic guided waves in stainless steel pressure vessels, with a focus on their interaction with corrosion-induced damage under internal pressure fluctuations. Through carefully controlled experiments, mode-specific amplitude and phase variations are analyzed to assess their sensitivity to damage evolution. The research further proposes an autonomous SHM framework that leverages guided wave sensing for real-time condition assessment and predictive maintenance. By bridging the gap between laboratory investigations and industrial deployment, the work aims to advance the development of intelligent, robust, and scalable monitoring solutions for critical pressure-bound systems.

1.1 Research Gap and Scope of the Present Study

Pressure vessels are extensively used in critical infrastructure, including hydrogen energy systems, cryogenic storage, and petrochemical processing. Despite the availability of established non-destructive evaluation (NDE) techniques, such as conventional ultrasonic testing, magnetic particle inspection, and radiography, these methods typically operate in an offline mode, requiring manual intervention and scheduled downtimes. As a result, they often fail to provide timely warnings of progressive defects, especially those caused by corrosion—a leading cause of structural degradation in pressurized systems operating under harsh environments. Recent advancements in structural health monitoring (SHM) have introduced ultrasonic guided waves as a promising tool for long-range inspection and real-time damage detection. However, much of the existing research has focused either on pipelines or flat plates, with limited attention given to the complex geometries and boundary conditions inherent to pressure vessels. Furthermore, studies that incorporate the dynamic effects of internal pressure variations on guided wave propagation remain sparse. This presents a significant knowledge gap, especially in understanding how guided wave modes interact with evolving corrosion damage under fluctuating operational loads.

The present study addresses these limitations by systematically investigating the behavior of guided waves in stainless steel pressure vessels subjected to localized corrosion. It aims to identify the wave modes most sensitive to such defects and to assess how their propagation characteristics are influenced by internal pressure changes. Through a combination of controlled laboratory experiments and autonomous signal analysis, the study seeks to develop a robust and intelligent SHM framework that enables early damage detection and predictive maintenance. By filling this critical gap, the research contributes to the development of reliable, real-time monitoring solutions that can be integrated into next-generation pressure vessels used in demanding industrial sectors. This will enhance safety margins, reduce maintenance costs, and improve the operational lifespan of pressurized systems.

2. FINITE ELEMENT MODELLING

This study employs finite element (FE) analysis to simulate the propagation of ultrasonic guided waves (guided waves) in a stainless steel pressure vessel, with the objective of understanding wave–defect interactions and the influence of internal pressure on wave behavior. The simulations are performed using **ABAQUS/Explicit**, which is well-suited for handling high-frequency wave dynamics and transient responses. The geometry of the pressure vessel is modeled as a cylindrical shell with hemispherical end caps, representative of typical industrial configurations. A segment of the vessel with a length of 400 mm and an outer diameter of 300 mm is considered to balance computational efficiency with realistic spatial representation. The wall thickness is set to 8 mm, consistent with standard stainless steel pressure vessels used in hydrogen storage and cryogenic applications. The full 3D model is prepared in ABAQUS for further meshing and transient guided wave propagation simulation.

To capture the high-frequency guided wave modes (primarily S0 and A0 Lamb modes), the mesh is refined with a global seed size of 0.5 mm, ensuring a minimum of 20 elements per wavelength for accurate resolution. Reduced integration solid elements (*C3D8R*) are used to maintain computational efficiency without compromising the fidelity of wave propagation.

Excitation is applied through surface-mounted piezoelectric actuators, modeled as point displacement inputs with a 5-cycle Hanning-windowed tone burst centered at 150 kHz. Wave signals are recorded at multiple receiver points distributed along the vessel surface. Artificial corrosion defects are introduced as localized wall-thickness reductions, with varying depths and sizes to investigate their effect on wave scattering, mode conversion, and amplitude attenuation. Boundary conditions are carefully selected to reflect realistic constraints. The vessel ends are fixed to mimic clamped conditions, while internal pressure loads are applied to assess their impact on guided wave propagation under operational stresses.

The FE simulations provide insights into wave velocity variations, attenuation patterns, and mode sensitivity to defect geometry and internal loading. These results are used to inform the experimental design and to optimize sensor placement for real-time structural health monitoring applications. The FE model is presented in Figure 1 and the material properties of the stainless steel pressure vessel are presented in Table 1

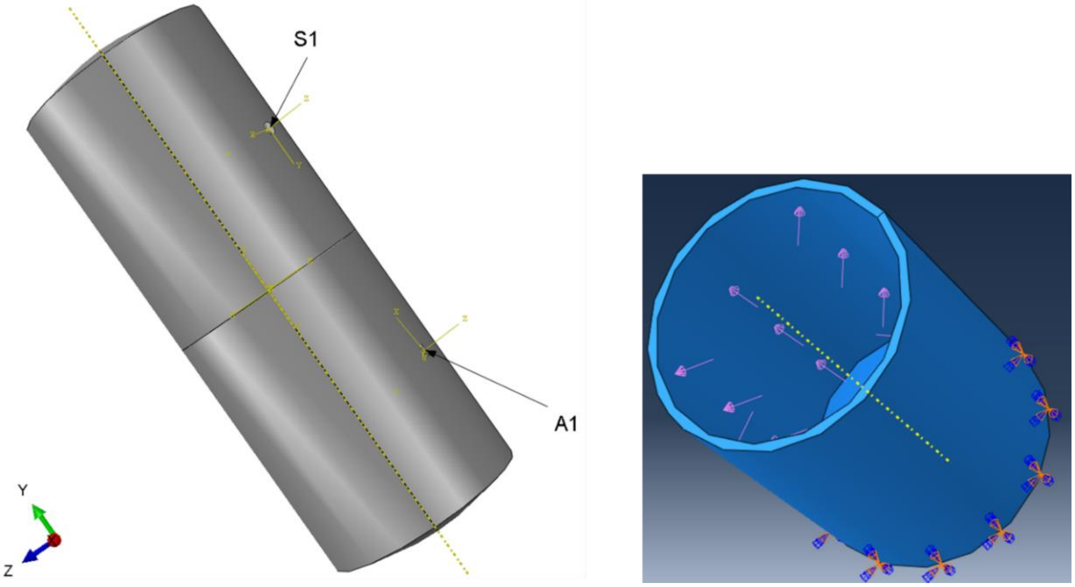


Figure 1: FE model of the pressure vessel in ABAQUS.

Table 1: Material properties of the pressure vessel.

Property	Symbol / Units	Value
Density	ρ (kg/m^3)	8000
Young’s Modulus	E (GPa)	193 – 200
Poisson’s Ratio	ν	0.28 – 0.30
Shear Modulus	$G = E / [2(1+\nu)]$ (GPa)	75

3. RESULTS AND DISCUSSION

This This section presents and analyzes the findings obtained from the finite element simulations and the subsequent deep learning-based classification framework. The study primarily focuses on evaluating the effectiveness of ultrasonic guided wave signals in detecting internal-wall corrosion in stainless steel pressure vessels under varying internal pressure conditions. Figure 2 illustrates a representative waveform plot, highlighting the region affected by internal corrosion within the pressure vessel model. These simulations reveal discernible changes in the guided wave response due to the presence of localized wall-thickness reduction. To establish a baseline, Figure 3 displays the time-domain guided wave signals corresponding to a healthy vessel under different internal pressure levels. These waveforms serve as a reference for understanding the pressure-dependent variation in guided wave behavior in the absence of damage.

In contrast, Figure 4 presents the guided wave signals captured from the pressure vessel containing corrosion-induced defects, also under varying internal pressure conditions. A comparative analysis between Figures 3 and 4 indicates notable differences in signal amplitude, arrival time, and waveform characteristics—especially in the presence of defects. These variations are indicative of wave scattering and attenuation resulting from corrosion.

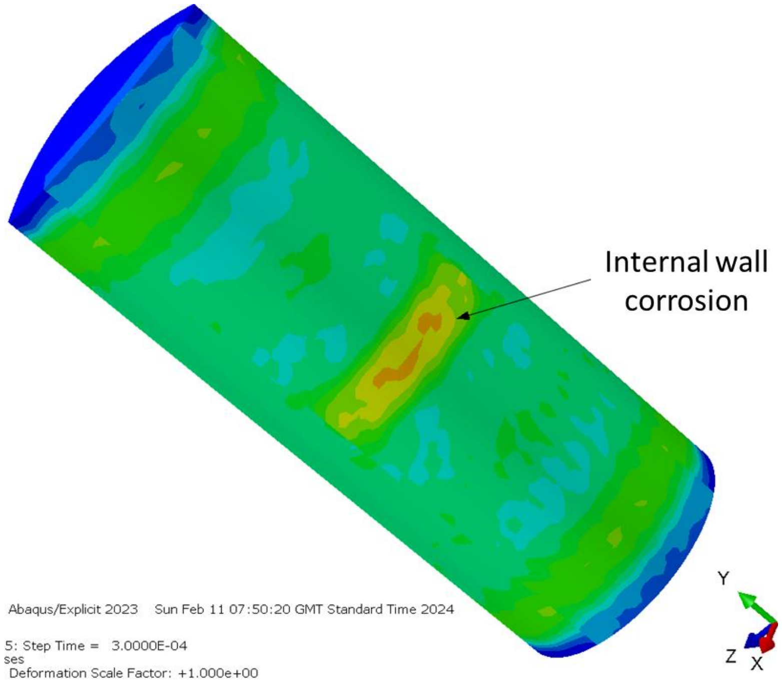


Figure 2: Waveform plot shows the internal-wall corrosion damage.

To further enhance the interpretability of the waveforms and extract robust features for automated damage identification, the time-domain signals are transformed into time-frequency representations using Continuous Wavelet Transform (CWT). The resulting scalograms, shown in Figure 5, capture the multi-resolution characteristics of the guided wave signals and provide a visual distinction between healthy and damaged states. These scalograms are then used as input features for a deep learning classification model based on the VGG16 convolutional neural network architecture. The model is trained to distinguish between healthy and corroded conditions using labeled datasets, and its performance is evaluated on previously unseen test samples. The classification results, illustrated in Figure 6, demonstrate the model's high accuracy and reliability in detecting internal-wall corrosion across a range of pressure scenarios. The combined FE and deep learning approach proves effective in capturing and classifying guided wave signal variations associated with structural degradation. The results validate the potential of integrating physics-based simulations with AI-driven pattern recognition for real-time and intelligent structural health monitoring of pressure vessels.

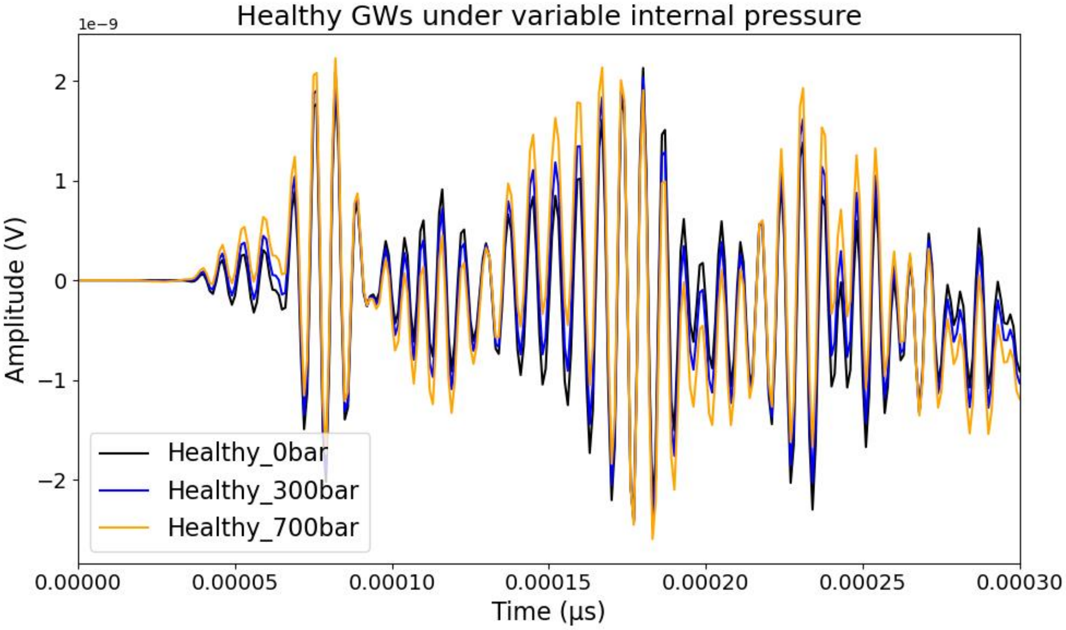


Figure 3: Guided wave signals corresponding to the healthy condition under variable internal pressure.

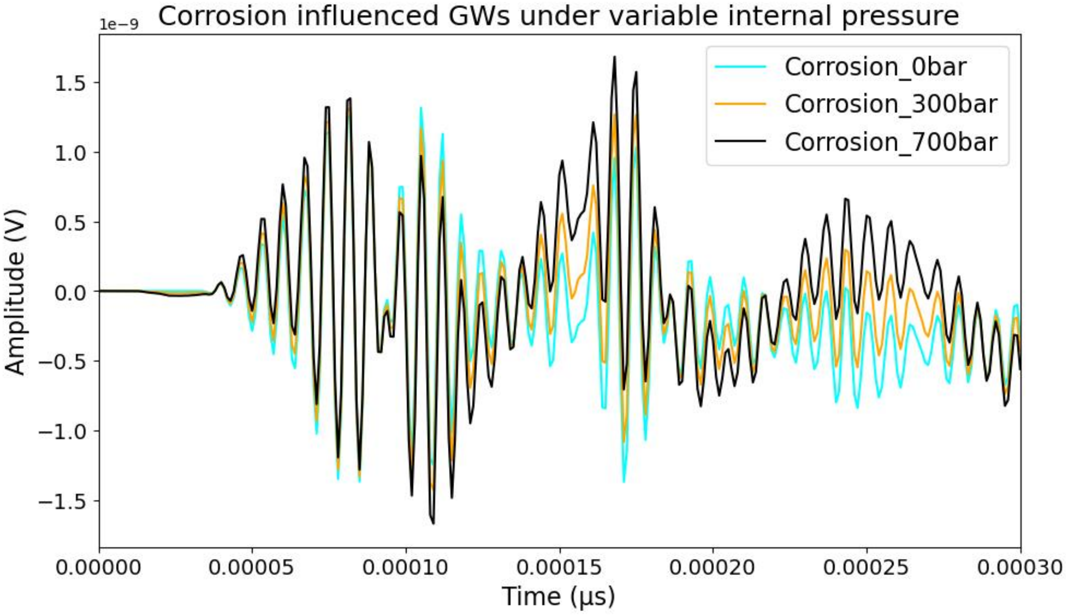


Figure 4: Guided wave signals corresponding to the corrosion damage condition under variable internal pressure conditions.

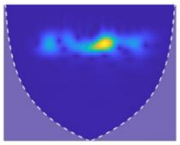
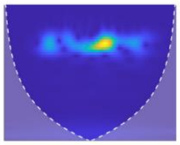
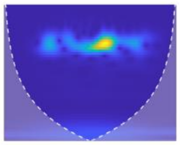
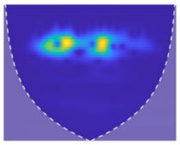
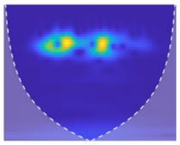
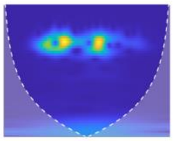
Condition	CWT Scalogram at 0 bar	CWT Scalogram at 300 bar	CWT Scalogram at 700 bar
Healthy			
Internal Corrosion			

Figure 5: Typical CWT scalogram images corresponding to the healthy and corrosion-damaged conditions.

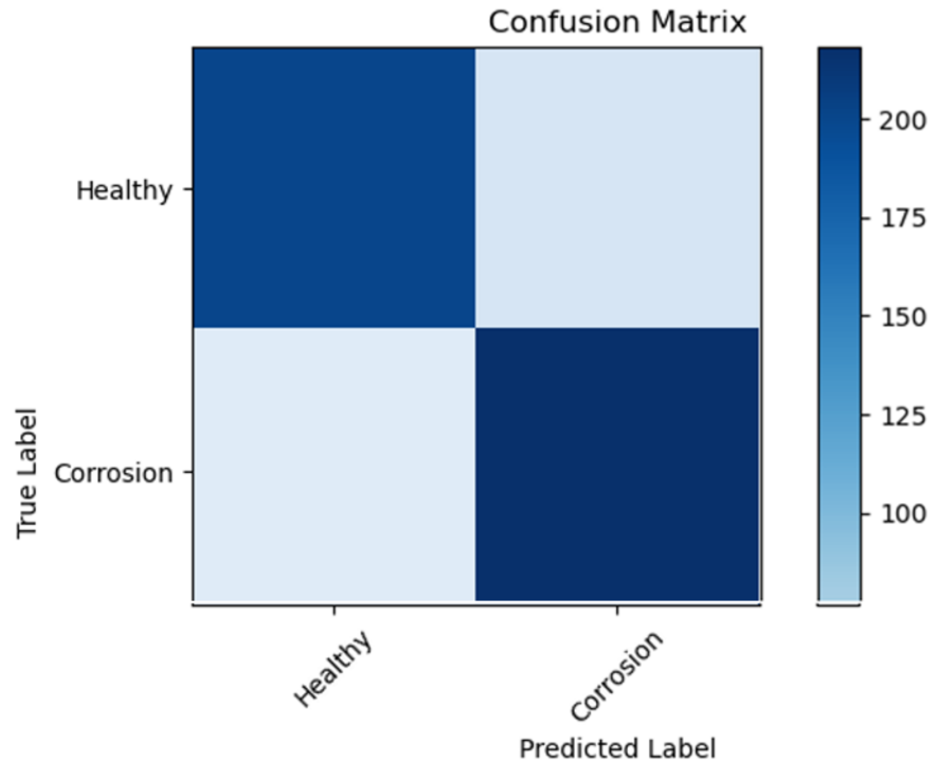


Figure 6: Test results from the deep learning model shows the high prediction accuracy for healthy and corrosion-damaged conditions of the pressure vessels.

4. CONCLUSION

This study explored the application of ultrasonic guided waves (UGWs) combined with deep learning techniques for the intelligent structural health monitoring (SHM) of stainless steel pressure vessels. Finite element simulations were conducted to model the propagation of guided waves under varying internal pressure conditions, both for healthy and corrosion-damaged states. The extracted time-domain signals were converted into time-frequency scalograms using Continuous Wavelet Transform (CWT), which were subsequently used to train a VGG16-based deep learning model. The integrated framework demonstrated high classification accuracy, highlighting its potential for real-time corrosion monitoring in critical industrial systems.

- Ultrasonic guided waves are sensitive to internal-wall corrosion and show measurable variations in amplitude and time-of-flight characteristics under operational pressure conditions.
- Finite element simulations effectively captured the wave–defect interactions and provided valuable insights into signal behavior under mechanical loading.
- The transformation of guided wave signals into CWT-based scalograms enhanced feature representation, allowing better discrimination between healthy and damaged states.
- The VGG16 deep learning model achieved reliable classification performance, indicating strong potential for automated defect detection in pressure vessels.
- The integration of physics-based simulations with data-driven models offers a scalable and robust approach for predictive maintenance in industrial environments.
- The proposed framework supports real-time, autonomous SHM applications, thereby improving safety, reducing unplanned downtime, and extending service life of pressure vessels.

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