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Evaluation of 3D-Printed PLA Couplers for Efficient Circumferential Ultrasonic Guided Wave Excitation on Composite Pipes

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Abstract

This study investigates the feasibility and performance of 3D-printed polylactic acid (PLA) couplers for generating and receiving circumferential ultrasonic guided waves (CUGWs) in glass-reinforced vinylester (GRV) composite pipes. The experimental system employs PLA couplers in conjunction with a water couplant, ensuring stable and repeatable acoustic coupling. The longitudinal wave velocity of the 3D-printed PLA was characterized to enable accurate delay compensation, and the propagation of guided waves in the composite pipe was analyzed at multiple circumferential positions and frequencies (120, 200, and 400 kHz). The results show that the dominant modes exhibit low dispersion, making them particularly suitable for inspection purposes. Mode separation analysis allows determination of group velocities for individual modes, highlighting the influence of fiber orientation on wave propagation. The study demonstrates that PLA-based couplers provide a low-cost, flexible, and customizable solution for generating and optimizing guided-wave modes, and can be tailored for various pipe geometries and inspection requirements. The findings highlight the potential of additive-manufactured polymeric couplers for advanced non-destructive evaluation of composite piping systems.

Keywords: Circumferential guided waves; PLA coupler; composite pipes; ultrasonic testing; mode optimization

1. Introduction

Polymeric composites are widely used in engineering applications due to their exceptional mechanical properties, including high stiffness, strength, low weight, corrosion resistance, and fatigue durability. These composites are utilized in various industries such as petrochemical, oil and gas and transmission lines of different fluids. Glass fiber reinforced pipes (GFRP/GRP) and tanks have lower maintenance costs and high corrosion resistance, which makes them the main candidate for replacing metallic piping structures [1]. GRPs consist of glass fibers and a polymer matrix, and based on their matrix resin, they are categorized into three common groups of glass fiber reinforced polyester, vinyl ester, or epoxy (GRP, GRV, and GRE) pipes.

Non-destructive testing (NDT) techniques are widely used to evaluate composite pipes and their joints during manufacturing and service [2]. Previous studies have reviewed damage types, inspection challenges, and recent NDT advancements for FRP and GRP structures, including the use of radiographic methods for joint and pipe inspection [3-8].

Ultrasonic testing (UT) is a common non-destructive method that uses high-frequency acoustic waves to detect internal flaws and assess material integrity [9-11]. However, inspection of anisotropic composite structures is challenging due to wave scattering and attenuation. Advanced approaches such as Phased Array Ultrasonic Testing (PAUT) improve sensitivity and speed, and can be integrated with Structural Health Monitoring (SHM) systems for real-time evaluation [12]. Among ultrasonic-based approaches, guided wave ultrasonic testing (GWUT) has emerged as an effective long-range inspection method for rapid defect detection in pipelines and joints [13].
Ghavamian et al. [14] reviewed experimental and simulation studies on defect detection and localization in pipelines using guided ultrasonic waves, which have been successfully applied in the oil and gas industries over the past two decades. They discussed various simulation techniques, attenuation behavior, signal processing, and transducer configurations. The propagation of guided waves in multilayered composite structures exhibits multiple modes and dispersion characteristics. Yang and Wu [15] analyzed guided wave propagation in composite pipes using a semi-analytical finite element (SAFE) method and validated their results with ABAQUS simulations and experimental group velocity measurements. Similarly, Gresil et al. [16] studied guided wave modes in epoxy hybrid carbon/glass fiber pipes through finite element simulations and experiments, focusing on longitudinal L(0,n) and torsional T(0,n) axisymmetric modes. Padiyar and Balasubramaniam [11] employed the A0 Lamb mode using non-contact air-coupled transducers to detect artificial inclusions in GFRP pipes, demonstrating a two-step inspection approach. Jozani and Soorgee [17] numerically simulated the L(0,1) guided mode to assess adhesive integrity in composite pipes and performed a parametric study to identify suitable signal features for damage detection.

Circumferential guided waves are a class of elastic waves that propagate along the circumference of cylindrical structures and can be categorized into circumferential shear horizontal (CSH) and circumferential Lamb-type (CLT) modes. Initially, circumferential guided waves were modeled using plate approximations until Liu [18] developed a comprehensive formulation for circumferential Lamb waves. Valle et al. [19] investigated the propagation of circumferential guided waves in cracked isotropic cylinders, while Wang et al. [20] analyzed circumferential shear horizontal (CSH) wave behavior in pipelines using reflection and transmission coefficients to evaluate axial cracks. Additional research has also been reported on the propagation of CSH waves in pipes [21, 22].

In recent years, the design of wedges and couplers has played a critical role in enhancing the efficiency and selectivity of ultrasonic guided wave inspection. Conventional couplers, such as Lucite or acrylic wedges, are commonly used for generating specific Lamb or circumferential wave modes but are often expensive and limited by fixed geometries and incidence angles [23]. Studies have shown that optimized wedge designs, including variable-angle and comb-type configurations, can improve mode selectivity and simplify signal interpretation [23-25]. For example, Shivaraj et al. [26] demonstrated the capability of an acrylic wedge-based system to detect pitting-type corrosion in inaccessible pipe-support locations using circumferential guided waves. However, such commercial wedges are typically metallic or polymeric with limited adaptability for different pipe materials and geometries. Additive manufacturing (AM), particularly 3D printing with polymeric materials such as polylactic acid (PLA), provides a low-cost and flexible alternative for fabricating customized couplers. PLA couplers can be tailored in shape and acoustic impedance, enabling better coupling with curved composite surfaces and potentially allowing mode control through design optimization [23]. Despite these advantages, studies exploring the performance of 3D-printed polymer couplers for circumferential guided wave generation in composite pipes remain limited. Therefore, this study aims to experimentally evaluate a 3D-printed PLA coupler for generating and receiving circumferential guided waves in composite pipes. The feasibility of this coupler is assessed by analyzing wave propagation characteristics and group velocity measurements.

2. Design and Development of the Ultrasonic Inspection System

2.1 System configuration and coupling mechanism

The system is designed to generate and measure circumferential ultrasonic guided waves (CUGWs) in composite pipes. As shown in Fig. 1a, it employs 3D-printed polylactic acid (PLA) shoes as acoustic couplers between the transducers and the pipe surface. The couplers are mounted on a supporting ring mechanism that ensures rigid fixation, axial alignment, and controlled circumferential positioning. To maintain stable and repeatable coupling, water was selected as the coupling medium instead of conventional gel, which showed inconsistent transmission during preliminary tests. The shoes were therefore designed with integrated inlet–outlet channels to sustain continuous water circulation, forming a uniform water film of approximately 1 mm at the shoe–pipe interface (Fig. 1b–c).

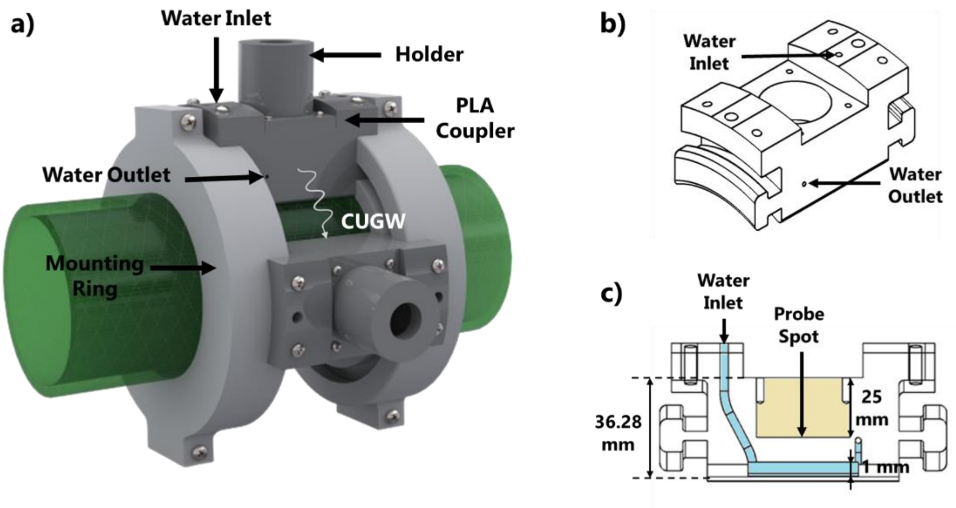

Figure 1. (a) Experimental setup for CUGW propagation in the pipe, (b) designed PLA coupler for transducer mounting, and (c) water channels showing the water film region.

The couplers were manufactured using fused deposition modeling (FDM) with 100% infill density to ensure structural stiffness and minimize acoustic scattering inside the material. A 200 µm layer height was selected as an optimized trade-off between surface smoothness and fabrication time. This additive manufacturing approach enabled precise geometric conformity to the pipe curvature and transducer dimensions, promoting repeatable wave transmission performance.

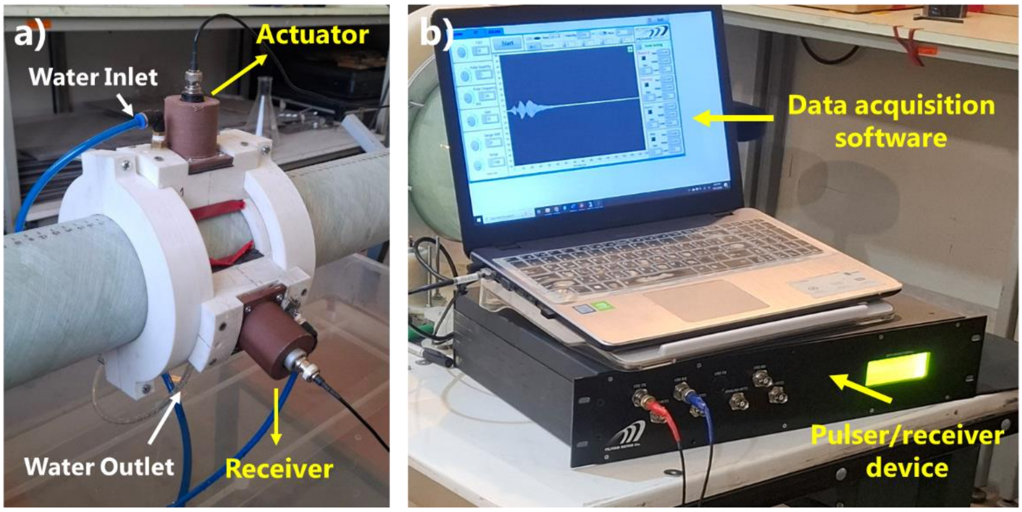

Figure 2. (a) Experimental test setup for CUGW inspection; (b) ultrasonic pulser/receiver hardware and data acquisition software used for signal generation, recording, and monitoring.

The complete experimental bench, including the pulser/receiver unit, data acquisition interface, and mounted PLA couplers, is shown in Fig. 2.
The specimen investigated in this study was a Glass-Reinforced Vinylester (GRV) composite pipe with an outer diameter of 112 mm and a wall thickness of 7 mm. The laminate was fabricated with a stacking sequence of $[0, \pm 63_3]$, consisting of one inner Felt layer and six Vinylester-glass layers alternately oriented at ±63°. This lay-up configuration was designed to enhance the hoop stiffness and optimize the propagation of guided waves along the circumferential direction.

2.2 Characterization of Longitudinal Wave Velocity in 3D-Printed PLA

To accurately predict wave transmission through the printed PLA coupler and determine the required time delay compensation in the inspection system, it is essential to measure the longitudinal wave velocity along the actual propagation direction inside the coupler. Because FDM-printed PLA exhibits direction-dependent mechanical behavior, the wave speed was characterized specifically along the printing path aligned with the acoustic propagation axis in the coupler.
FDM-fabricated thermoplastic parts such as PLA are widely reported to present anisotropic or orthotropic elastic behavior due to filament deposition architecture and interlayer bonding characteristics. This has been confirmed in numerous studies demonstrating orientation-dependent acoustic and mechanical properties of PLA manufactured by FDM [27-29]

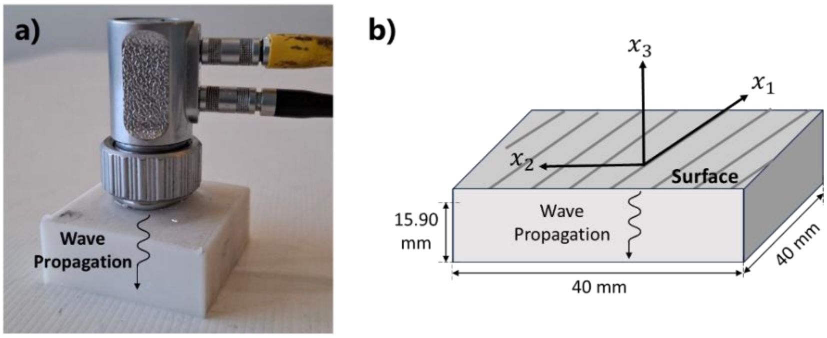

Figure 3. (a) Cubic PLA specimen with the pulse-echo transducer mounted; (b) specimen dimensions and FDM printing orientation.

The longitudinal wave velocity was measured using a pulse-echo technique with a 2 MHz dual-element transducer. The cubic PLA specimen and experimental configuration are shown in Fig. 3a, while Fig. 3b presents the sample geometry, dimensions, and printing orientation relative to the wave propagation axis. The precise specimen thickness allowed direct calculation of wave speed from the time spacing between consecutive back-wall echoes, eliminating manual arrival-time identification. The measured echo separation of approximately 15.9 μs corresponded to a longitudinal wave velocity of 1919.7 m/s along the printing direction (Fig. 4).

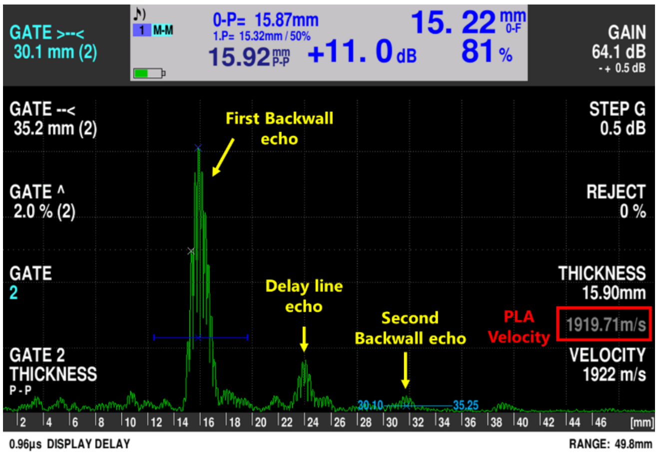

Figure 4. Received pulse-echo signal from the cubic PLA specimen, showing the filtered signal, its envelope, and the detected 3 dB arrival point.

With the longitudinal wave velocity of the 3D-printed PLA coupler determined, the system is now fully characterized, enabling accurate evaluation of circumferential guided wave propagation in composite pipes, as presented in the following section.

2.3 Delay Compensation in the Inspection Setup

As illustrated in Fig. 5, the circumferential ultrasonic guided wave (CUGW) generated by the system first propagates through the 3D-printed PLA coupler, then traverses the intermediate water coupling layer, and finally enters the pipe, where it propagates along the circumferential path. Each of these stages contributes a fixed time delay before the wave effectively travels within the pipe wall. The transmission time through the coupler and water layer constitutes a systematic delay inherent to the experimental setup.

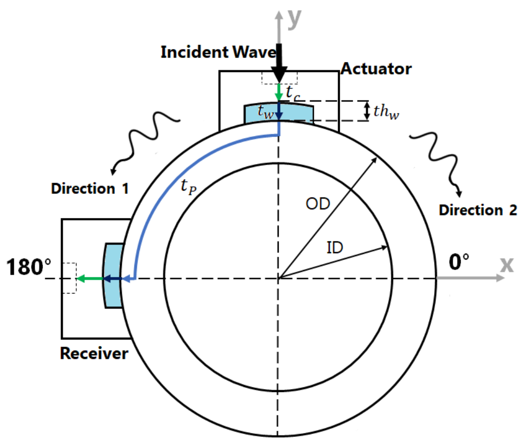

Figure 5. Schematic of the CUGW test setup, showing the delay line, propagation path, and pipe dimensions (not to scale).

This delay occurs at both the actuator and receiver sides and must be accounted for to accurately determine the propagation time of the guided wave in the pipe. The delay associated with a single coupling path can be expressed as:

$$t_{probe} = t_{PLA} + t_w. \tag{1}$$

Using the experimentally determined longitudinal wave velocity of the 3D-printed PLA and the known acoustic velocity in water, with a 1-mm water film, the delay introduced by one coupling path was calculated to be 6.30 μs. This value represents the portion of the measured signal time attributable solely to the coupler and water layer, prior to the wave entering the pipe.
Since identical couplers are used on both the actuator and receiver, the system exhibits a two-way delay that does not correspond to actual wave propagation inside the pipe. If uncorrected, this fixed delay would result in an overestimation of the guided wave travel time and, consequently, inaccuracies in group velocity and dispersion analyses. By subtracting this system delay from the total measured arrival time, the remaining time corresponds exclusively to the circumferential guided wave propagation within the pipe wall. This corrected propagation time forms the basis for all subsequent wave velocity calculations and dispersion characterization.
The overall correction applied in the analysis is summarized as:

$$t_p = t_{total} - 2 \times t_{probe}. \tag{2}$$

This approach effectively isolates the wave travel time within the pipe from the non-propagating contributions of the coupler and water layer, ensuring accurate evaluation of CUGW propagation in composite pipe structures.

3. Experimental Signal Analysis

During the experiments, the transmitter was fixed at the 90° circumferential position with respect to the pipe axis, as illustrated in Fig. 1-a and Fig. 5. Tests were carried out at three excitation frequencies, 120 Hz, 200 Hz, and 400 Hz, in order to examine the frequency-dependent propagation characteristics of guided waves in the composite pipe.
Because of the complex dispersion behavior of guided waves in anisotropic composite structures, the dominant modes observed in this study differ from those in isotropic cylindrical shells. For clarity, the circumferential mode notation (n) is employed to identify the propagating modes. The inherent anisotropy of the composite material results in direction-dependent wave velocities and dispersion characteristics, as reported by Yang & Wu [30]. Furthermore, attenuation in fiber-reinforced composites is typically higher than in isotropic metals, leading to greater wave damping and reduced propagation distance.
The received signals were measured at two receivers located at equal angular distances of 130° from the transmitter. As shown in Fig. 5, the waves reach the receiver at 220° primarily via Direction 1, whereas they propagate to the 320° receiver along Direction 2, as illustrated. Despite these distinct propagation paths, the recorded signals are highly similar in both shape and amplitude. This resemblance can be attributed to the dominant guided-wave modes, which considering the main modes depicted in Fig. 6, exhibit closely matched group velocities along both paths. Consequently, the arrival times and waveform patterns at the two receivers are nearly identical, reflecting the quasi-uniform propagation characteristics of the principal modes within the composite pipe. It should be noted that the signals have been corrected to remove the probe delay, ensuring that the comparison reflects the actual propagation characteristics without measurement-induced timing offsets.

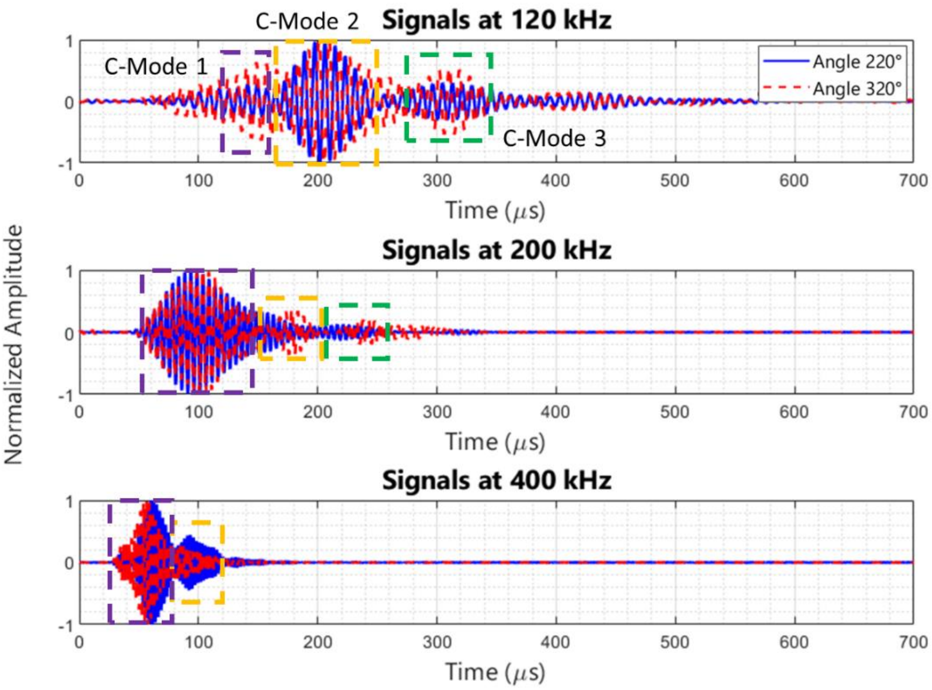

Figure 6. Filtered signals recorded at receivers positioned at 220° and 320° on the pipe, with the actuator set at 90°.

Considering the geometry of the couplers and the configuration of the water channels, the closest feasible position for probe placement is at an angle of 160°. In Fig. 7, the signals recorded at 160° and 220° are presented, clearly illustrating the presence of several non-dispersive modes generated within the composite pipe.

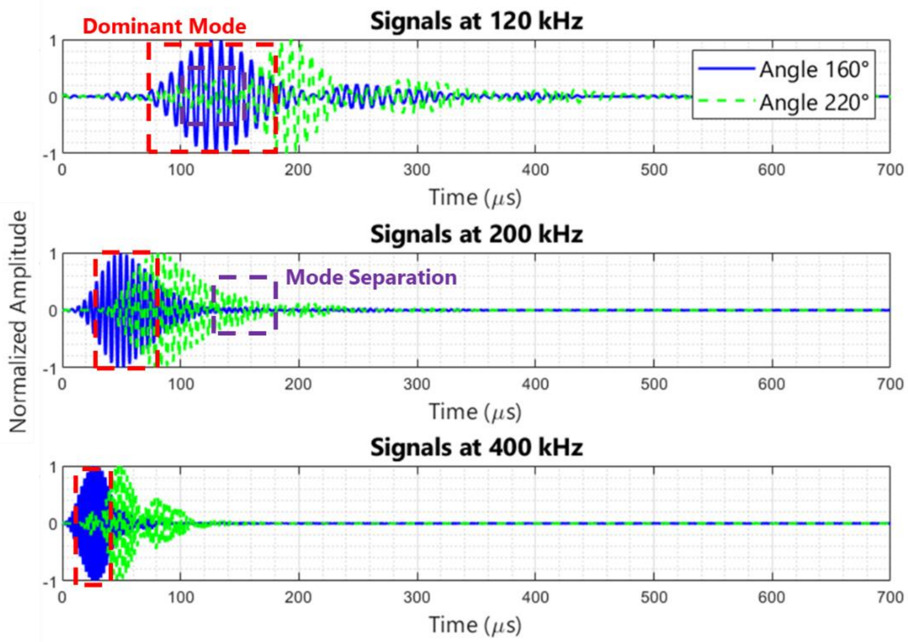

Figure 7. Filtered signals recorded at receivers positioned at 160° and 220° along the pipe circumference, with the actuator set at 90°.

As observed, at a frequency of 120 kHz, the modes exhibit significant dispersive behavior, which is also evident at 200 kHz. In contrast, at 400 kHz, the modes are less dispersive and fewer in number. These observations indicate that the higher frequency guided-wave modes propagate more uniformly, with reduced dispersion and simplified mode structures, facilitating clearer signal interpretation. Furthermore, some of the modes, as can be seen in the figure, are separated from the main signal and propagate at higher velocities, indicating that they possess larger group velocities.
In the following section, the group velocities of the principal guided-wave modes, which exhibit lower dispersion and can be clearly distinguished, are calculated. This analysis enables a more detailed characterization of the wave propagation within the composite pipe, providing quantitative insight into the dynamic behavior of the dominant modes.

4. Results and Discussion

Now, considering the dominant peaks shown in Figure 7, the group velocity can be calculated. This velocity is determined by finding the arrival time through the maximum of the envelope. The group velocity is then obtained by dividing the probe delay and taking into account the distance between the transmitter and receiver.
For two orientations, at 160° and 220°, the group velocity was calculated, as shown in Figure 8. As can be observed, the group velocities are close to each other, and the slopes of the dispersion curves for both orientations are similar. Therefore, within this frequency range, the dispersion curve of the group velocity can be obtained.

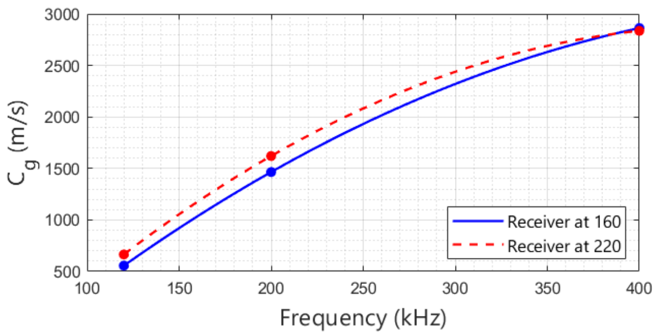

Figure 8. Group velocities of the dominant CGUW mode measured at circumferential positions of 160° and 220°.

The differences in the measured group velocities, in addition to experimental errors, may be attributed to the fiber orientation and the surface conditions of the pipe at the sensor location. Due to the winding pattern, the thickness may slightly vary in different regions, and the surface conditions also differ accordingly.
Now, by analyzing the modes and their separation at different orientations and subsequently calculating their group velocities, it is possible to determine the group velocity for each specific mode. For the modes identified in Fig. 6, the corresponding group velocities were calculated and are presented in Fig. 9.
As illustrated in Fig. 9, the dominant mode exhibits significantly lower dispersion, making it particularly suitable for inspection applications. Indeed, the fundamental mode is often preferred in guided-wave techniques due to its relatively constant group velocity over a useful frequency range, which helps to avoid pulse spreading and simplifies signal interpretation.
In light of this behaviour, a polymer-based coupler (PLA) in conjunction with a water couplant can be employed to excite multiple guided-wave modes. By altering the system configuration—such as probe orientation, spacing, and excitation parameters, it is possible to tailor these modes for specific inspection needs. In effect, the ultrasonic probe arrangement and excitation scheme can be configured

and optimized to excite a preferred mode that maximizes inspection range, sensitivity, or resolution according to the geometry and material of the inspected component.

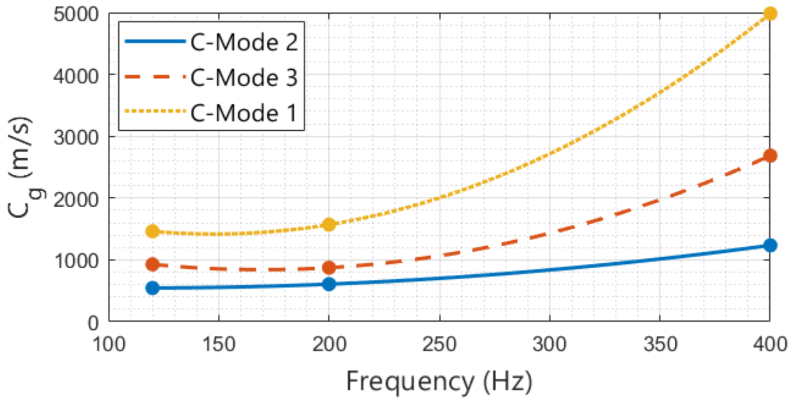

Figure 9. Group velocities of identified circumferential guided-wave modes in the GRV pipe

5. Conclusions

This work demonstrates the effectiveness of 3D-printed PLA couplers for the generation and reception of circumferential guided waves in composite pipes. The experimental results confirmed that the PLA couplers, combined with a water couplant, provide stable and repeatable acoustic transmission while allowing customization for different pipe geometries and transducer configurations. Analysis of guided-wave propagation revealed that the dominant modes exhibit low dispersion, enabling reliable inspection and simplified signal interpretation. Mode-specific group velocity measurements highlighted the influence of fiber orientation, local wall thickness, and surface conditions on wave propagation, providing valuable insights for accurate defect detection. Furthermore, the use of additive manufacturing allows the design of optimized couplers tailored for specific guided-wave modes, offering flexibility in inspection strategies and system configurations. Overall, this study establishes 3D-printed PLA couplers as a versatile, low-cost, and effective solution for non-destructive evaluation of polymeric composite pipelines, with potential for further optimization to enhance sensitivity, range, and mode selectivity in practical industrial applications.

REFERENCES

1. Rafiee, R., *On the mechanical performance of glass-fibre-reinforced thermosetting-resin pipes: A review.* Composite Structures, 2016. **143**: p. 151-164.
2. Ibrahim, M., *Nondestructive evaluation of thick-section composites and sandwich structures: A review.* Composites Part A: Applied Science and Manufacturing, 2014. **64**: p. 36-48.
3. Waqar, M., et al., *Composite pipelines: Analyzing defects and advancements in non-destructive testing techniques.* Engineering Failure Analysis, 2023: p. 107914.
4. Thon, H. and B.r. Melve. *Non-Destructive Evaluation of Composite Pipes and Tanks: Development of Inspection Strategies*. in *International Conference on Offshore Mechanics and Arctic Engineering*. 2004.
5. Silva, W., et al., *X-ray imaging techniques for inspection of composite pipelines.* Micron, 2021. **145**: p. 103033.
6. Rique, A., et al., *X-ray imaging inspection of fiberglass reinforced by epoxy composite.* Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms, 2015. **349**: p. 184-191.
7. Ferreira, C., et al., *Non-destructive inspection of laminated pipe joints in polymeric composite material reinforced by fiberglass.* Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment, 2020. **954**: p. 161154.
8. OLIVEIRA, D.F., S.D. SOARES, and R.T. LOPES. *Inspection of Composite Pipelines using Computed Radiography*. in *5th Pan American Conference for NDT. Cancun, Mexico*. 2011.

9. Carrino, S., A. Maffezzoli, and G. Scarselli, *Active SHM for composite pipes using piezoelectric sensors.* Materials Today: Proceedings, 2021. **34**: p. 1-9.
10. Joas, S., et al. *CFRP pipe inspection by means of air-coupled ultrasound*. in *AIP Conference Proceedings*. 2019. AIP Publishing LLC.
11. Padiyar, M. and K. Balasubramaniam, *Lamb wave-based air-coupled ultrasonic inspection technique for filament-wound composite pipes.* Insight-Non-Destructive Testing and Condition Monitoring, 2014. **56**(4): p. 195-202.
12. Taheri, H. and A.A. Hassen, *Nondestructive ultrasonic inspection of composite materials: A comparative advantage of phased array ultrasonic.* Applied Sciences, 2019. **9**(8): p. 1628.
13. Kang, T., et al., *Enhancement of detecting defects in pipes with focusing techniques.* NDT & e International, 2011. **44**(2): p. 178-187.
14. Ghavamian, A., et al., *Detection, localisation and assessment of defects in pipes using guided wave techniques: A review.* Sensors, 2018. **18**(12): p. 4470.
15. Yang, Z. and Z. Wu. *Guided waves dispersion analysis in composite pipe using the safe method*. in *European Workshop on Structural Health Monitoring: Special Collection of 2020 Papers-Volume 1*. 2021. Springer.
16. Gresil, M., A. Poohsai, and N. Chandarana, *Guided wave propagation and damage detection in composite pipes using piezoelectric sensors.* Procedia Engineering, 2017. **188**: p. 148-155.
17. Soorgee, M.H. and S. Jouzani, *Numerical Damage Detection in Composite Pipe Adhesive Joints Using Ultrasonic Guided Waves.* NDT Technology, 2020. **2**(6): p. 72-81.
18. Liu, G. and J. Qu, *Guided circumferential waves in a circular annulus.* 1998.
19. Valle, C., et al., *Crack characterization using guided circumferential waves.* The Journal of the Acoustical Society of America, 2001. **110**(3): p. 1282-1290.
20. Wang, S., et al., *3D modeling of circumferential SH guided waves in pipeline for axial cracking detection in ILI tools.* Ultrasonics, 2015. **56**: p. 325-331.
21. Zhao, X. and J.L. Rose, *Guided circumferential shear horizontal waves in an isotropic hollow cylinder.* The Journal of the Acoustical Society of America, 2004. **115**(5): p. 1912-1916.
22. Zhao, X., et al., *In-line nondestructive inspection of mechanical dents on pipelines with guided shear horizontal wave electromagnetic acoustic transducers.* 2005.
23. Balvantín, A.J., et al., *The suitability of using 3D PLA printed wedges for ultrasonic wave propagation.* IEEE Access, 2020. **8**: p. 15205-15209.
24. Park, M.H., I.S. Kim, and Y.K. Yoon, *Ultrasonic inspection of long steel pipes using Lamb waves.* NDT & E International, 1996. **29**(1): p. 13-20.
25. Rose, J.L., D. Jiao, and J. Spanner Jr, *Ultrasonics Guided Waves for Piping Inspection*, in *Review of Progress in Quantitative Nondestructive Evaluation: Volume 16A*. 1997, Springer. p. 1285-1290.
26. Shivaraj, K., et al., *Ultrasonic circumferential guided wave for pitting-type corrosion imaging at inaccessible pipe-support locations.* 2008.
27. Li, M., Y. Xu, and J. Fang, *Orthotropic mechanical properties of PLA materials fabricated by fused deposition modeling.* Thin-Walled Structures, 2024. **199**: p. 111800.
28. Parker, N., et al., *Longitudinal acoustic properties of poly (lactic acid) and poly (lactic-co-glycolic acid).* Biomedical Materials, 2010. **5**(5): p. 055004.
29. Pozhanka, M., et al., *Application of Ultrasonic Testing for Assessing the Elastic Properties of PLA Manufactured by Fused Deposition Modeling.* Applied Sciences, 2024. **14**(17): p. 7639.
30. Yang, Z. and Z. Wu. *Guided waves dispersion analysis in composite pipe using the safe method*. in *European Workshop on Structural Health Monitoring*. 2020. Springer.