



Guided Waves Propagation in Composite Overwrapped Pressure Vessel

Samir Mustapha^{1,2}, Bengisu Yilmaz², Jan Heimann², Blaz Brence² and Jens Prager²

¹Department of Non-Destructive Testing, Acoustic and Electromagnetic Methods Division, Bundesanstalt für Materialforschung und -Prüfung (BAM), Germany

²Department of Mechanical Engineering, American University of Beirut, Lebanon, sm154@aub.edu.lb

Abstract

The application of composite overwrapped pressure vessels (COPV) to store hydrogen and other compressed gases, especially when operating at high pressures, imposed the need for an innovative and reliable approach to ensure the safe operation of the system. Continuous structural health monitoring (SHM) based on ultrasonic guided waves (GWs) is a promising approach due to the ability of the wave to propagate for long distances and go around complex structures, moreover the high sensitivity to various failure modes such as delamination, matrix cracking and debonding. In this study, we scrutinize the behavior of (GWs) within the COPV using a network of PZT elements that are used for excitation and sensing. A laser doppler vibrometer (LDV) was also used to scan the surface of the vessel in various directions. L(0,1) and L(0,2) were observed in the captured signal. The L(0, 2) appeared to be a dominant mode in the COPV and was capable of propagating along the entire length and maintaining a good signal-to-noise ratio. The L(0,2) mode maintained the same phase velocity when it is captured at various excitation angles (0, 45, and 90 degrees). The reduced effect of the orthotropy of the materials on the propagating waves is an important result as it will reduce the complexity in data processing when performing damage identification.

KEYWORDS: Composite Overwrapped Pressure Vessels, Guided Waves, Laser Doppler Vibrometer, Structural Health Monitoring, Sensors Placement.

1. Introduction

Composite pressure vessels (CPV) have been widely used in many applications spreading across multiple disciplines including but not limited to automotive, and aerospace. Compressed natural gas and hydrogen are emerging as new energy sources and as alternatives to traditional ones, hence their storage is essential and must cater to the various intended future applications such as hydrogen cars and hydrogen fuelling stations where they may be as high as 700 bar [1]. The multi-layered nature of the composite lay-up used in the construction of the CPVs is associated with different failure modes, in comparison to traditional metallic structures such as low-velocity impact on the CPVs can cause delamination, fiber breakage, or matrix cracking [2].



The safe application of the CPVs requires the use of precise and reliable techniques to monitor the conditions during their lifetime. Several commercial techniques have been developed for the inspection of CPVs including but not limited to ultrasound, and vibration testing. These techniques can only be applied based on a regular inspection schedule, the operation of the vessels may need to be seized, and this requires experts to carry on the inspection. Continuous monitoring on the other hand can provide many other benefits besides damage detection and assessment, it allows for life prediction, can be used to improve the current design, and further extend the lifetime of the assets. Ultrasonic-guided waves (GVs) have proven to be a good tool to be applied as a part of an SHM system for several reasons, including the sensitivity of the guided waves to various types of defects, as well as the ability of the wave to propagate in curved structures and for long distances [3]. This study focuses on the understanding of the ultrasonics-guided waves propagation in composite pressure vessels (Type IV) towards the development of a sensor network to provide full coverage of the area under study. The rest of the paper is structured as follows, a methodology highlighting the main tools used in this study, followed by the results and discussion, and last but not least some concluding remarks.

2. Methodology

2.1 Guided waves in cylindrical structures

GWs have great potential for the detection of different types of damage on both the inner and outer surfaces of cylindrical sections [4]. Due to cylindrical curvature and dispersion characteristics, the propagated waves exhibit very complex multimodal behavior.

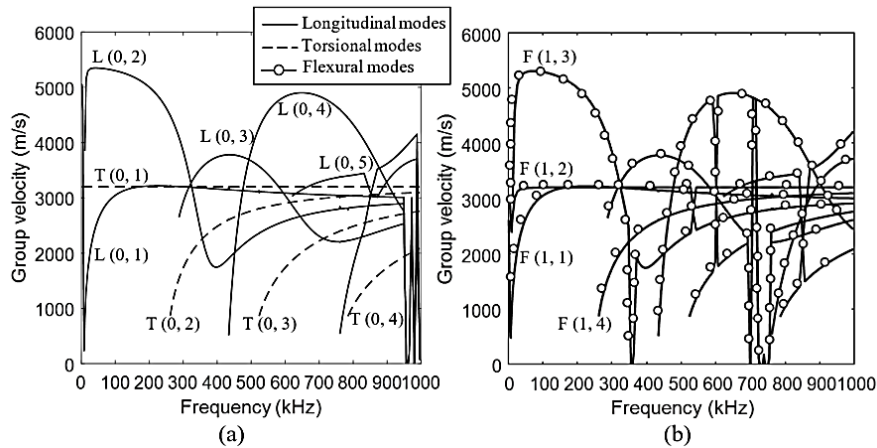


Figure 1. Group velocity dispersion curves in a pipe section in (a) longitudinal and torsional modes and (b) flexural modes.

The multimode GWs can propagate along different paths, including circumferential/flexural, longitudinal, and torsional, which refers to traveling through the thickness dimension [5]. The GWs modes were named $L(0,n)$, $T(0, n)$, and $F(m, n)$, according to [6, 7], which corresponded to the longitudinal, torsional, and flexural modes, respectively. The m stood for the circumference variation harmonic number and n was the wave mode order. The modes that span from zero frequency were the first mode. The other modes were given names that corresponded to the order of their cut-off frequency. Figure 1 displays the group velocity dispersion curves (for demonstration only) for a

schedule 20, 200-mm diameter ASTM A106 seamless pipe with a wall thickness of 6.35 mm using MATLAB code developed by Seco *et al.* [8].

2.2 Signal processing

An SLDV measures the out-of-plane velocity (\mathbf{v}) of the propagating waves at the surface of the monitored structure. Frequency-wavenumber (f - k) images can be produced from line scans along the directions of interest, which is important for capturing and analyzing the available wave modes. Considering a vertical line scan, the experimental f - k images can be generated by applying the two-dimensional temporal and spatial fast Fourier transform (FFT_{2D}) to the line-scan data $\mathbf{v}(y, t)$. The generated f - k images can be used to identify the wave modes, further helping in generating the phase velocity curves.

2.3 Experimental validation

In the first experiment, five sinusoidal cycles in an hanning window sampled at a rate of 3 MSa/s were generated using Multifunction DAQ from NI, then amplified to 300 volts peak-peak using a high voltage amplifier WMA-300. The generated signal was applied to a PZT ceramic 100 mm in diameter to excite the ultrasonic-guided waves (P-876K025). A row of seven PZTs ceramics spaced at 150 mm was placed on the pressure vessel using araldite adhesive (UHU plus schnellfest 2K-Epoxidharzkleber). A series of excitation frequencies were used ranging from 10 kHz to 250 kHz in a step of 5 or 10 kHz. The numbering of the PZT ceramic goes from 1-7 from left to right as shown in Figure 2.

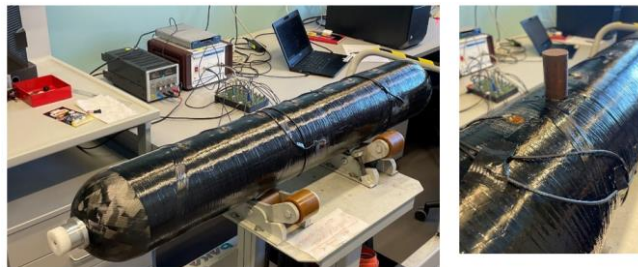


Figure 2- Tested pressure vessel with mounted PZT sensor network.

Another experiment was carried out using the laser scanner based on using a chirp excitation (Figure 3). The chirp signal, it had a frequency range of 20–500 kHz with a duration of 200 μ s [9]. The generated signal was fed to an Agilent 33521 arbitrary wave generator and amplified to 100 volts using a high-voltage amplifier (HVA-400-A, Ciprian) before feeding to PZT ceramic. The wavefield was recorded using a 3D scanning laser-Doppler vibrometer (PSV-500-3D-HV, Polytec). The scan length varied depending on the direction of scanning i.e. longitudinal, circumferential or diagonal.



Figure 3- 3D scanning on the COPV using the LDV.

3. Results and discussion

3.1 Dispersion curves

It is essential to generate the dispersion curves of the composite structures used to construct the pressure vessel. Using PZT 3 for excitation and PZT 5 for sensing (spaced at 300 mm), measurements were taken over a range of frequencies from 10 to 250 kHz. For each of the excitation frequencies, the modes (wave packages) have been identified and their group velocity was calculated using the time of flight and the known distance between the exciter and the receiver. The selection of the peak of the mode is not a straightforward task, especially when multiple modes are combined. Usually, after applying the Hilbert transform, the time of the peak of the wave pack is selected. When the peak is not clear, relying on the time of propagation of the first cycle, or second cycle can be used. Further to ensure the accurate selection of the mode, the wave packets were traced at various sensing positions.

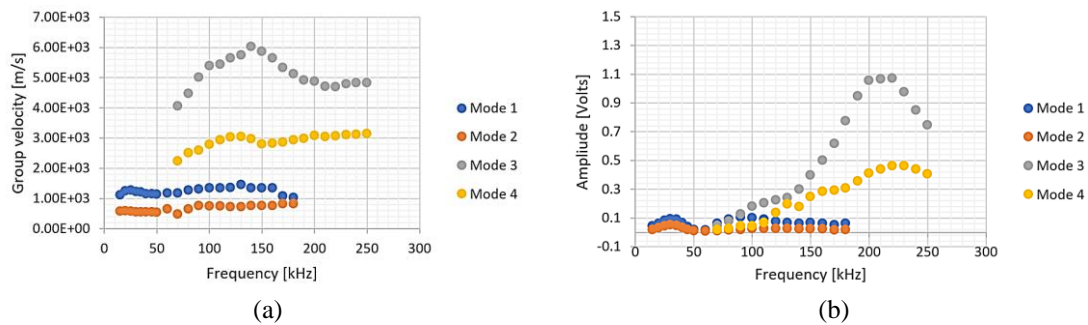


Figure 4 - Dispersion curves using experimental data - Based on data collected using PZT 5 (sensor) when exciting with PZT 3 (a) group velocity and (b) amplitude.

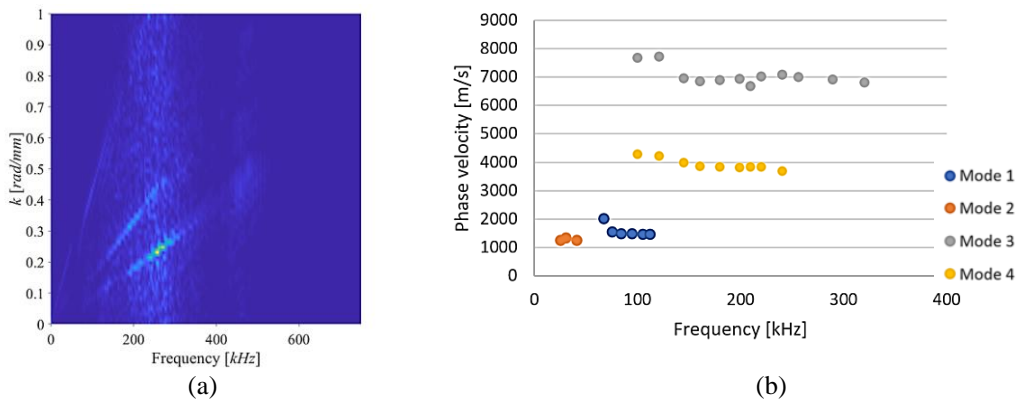


Figure 5 Phase velocity calculation (a) $f-k$ plot using the line scan along the longitudinal direction excited using the generated chirp signal (this is the total response of three lasers) (b) Phase velocities extracted using the $f-k$ plot in (a).

Four modes were identified, mode 1 and mode 2 are traveling at a slower speed than mode 3 and mode 4. Mode 1 and 2 were observed to have a linear behavior as the frequency increased, similarly for modes 3 and 4 above 180 kHz. Below 180 kHz, modes 3 and 4 showed a significant variation in the group velocity, as shown in Figure 4 (a), reaching a peak value of about 6000m/s at 140 kHz. Investigating the amplitude of the four modes detected, it was clear that modes 3 and 4 have much higher amplitudes than modes 1 and 2 as shown in Figure 4 (b). Modes 1 and 2 amplitude was very low above 50 kHz. Modes

3 and 4 have two peaks around 130 kHz (with multiple modes present) and at 220 kHz (with one dominant mode). Mode 3 was identified as the L(0, 2) mode, while mode 4 was L(0, 1).

Further, doing a line scan using the LDV using a chirp signal for a frequency range from 30 kHz to 500 kHz, the f - k plot was generated as shown in Figure 5 (a). Figure 5 (a) showed two wave modes propagating at low speed and at low frequency (identified as modes 1 and 2), in addition to another two modes that are propagating at a faster speed (modes 3 and 4, i.e. L(0, 1) and L(0,2) modes). This shows a consistency between the modes identified using the PZT measurements and the LDV line scans. Using the f - k plots, the phase velocity curves were also generated as displayed in Figure 5 (b) (using the following equation $Phase\ velocity = 2\pi f/k$, where k is the wave number).

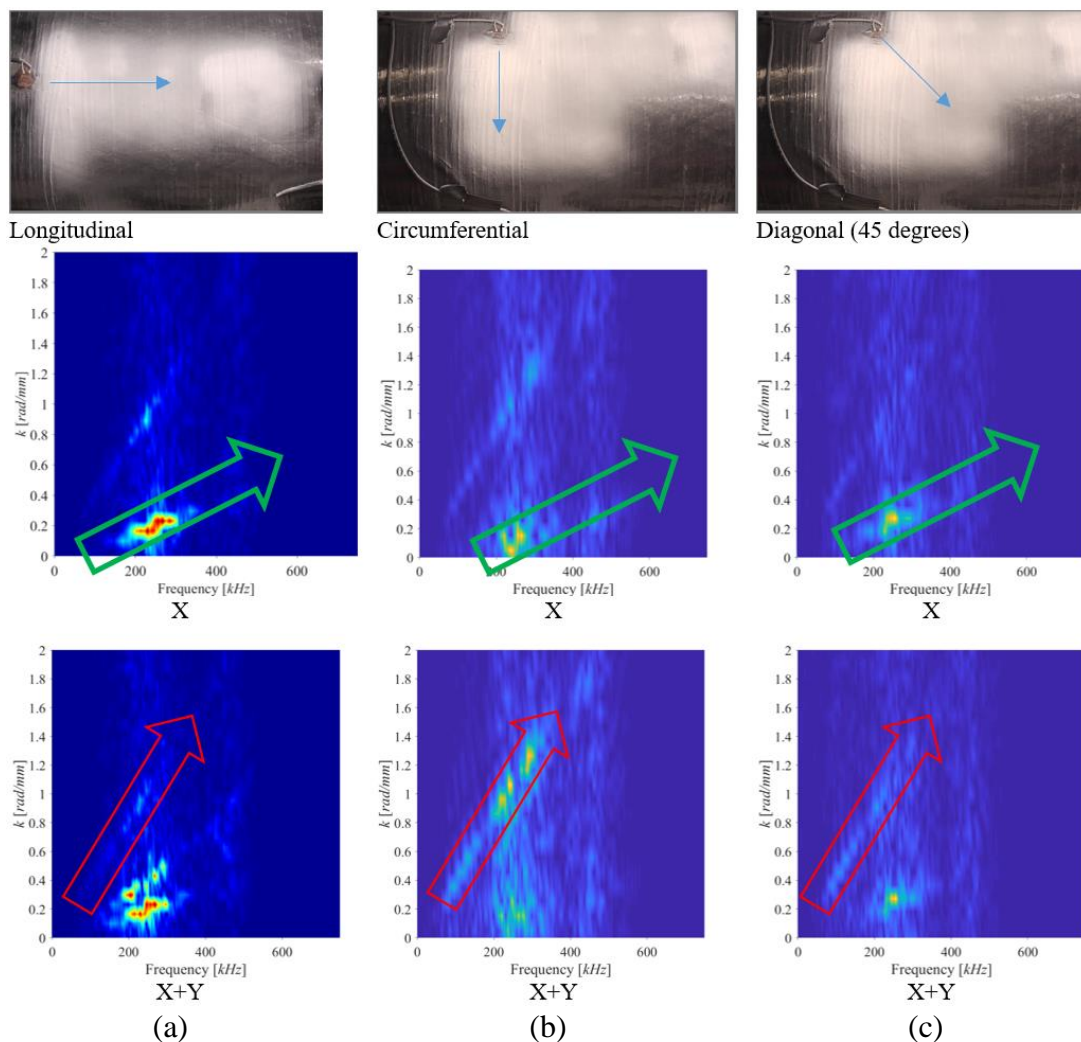


Figure 6 - f - k plot for the chirp excitation in various directions along the (a) longitudinal, (b) circumferential, and (c) diagonal directions.

3.2 Laser Line Scan in Different Directions

When talking about composite structures, we often connect this to orthotropic materials. There is a strong dependence between the mechanical properties of the materials and the

lay-up sequence of the fibers. Since the mechanical properties change with the direction or orientation of the fibers, hence the wave propagation characteristics (GWs) can also change. To better understand the excited modes in the CPW, a laser line scan is performed along the longitudinal, circumferential, and diagonal directions. **Error! Reference source not found.** shows the f - k images along the three scanning directions. Also, presents the combinations of the various lasers' responses to construct the f - k images. Combinations of the laser response may enhance the presence of certain modes depending on the nature of these modes (plane or out-of-plane). It was obvious the presence of two modes (modes 3 and 4) was indicated by the green and red arrows. More interestingly they have a similar slope, hence the phase velocity doesn't change with the direction, this may indicate that the lay-up is close to quasi-isotropic. Therefore, the quasi-isotropy of the materials can be assumed. Calculating the propagating speed of the first transmitted wave, it was found that the velocity varies around 5000 m/s depending on the PZT sensor used. A maximum variation of 2% is observed in the propagating speed (excluding a couple of excitation frequencies).

4. Conclusions

It was essential to understand some characteristics of the GWs within the composite overwrapped pressure vessel (COPV). Several wave modes were detected with two modes that appeared dominant traveling at two different speeds. We have selected the faster one. The sensitivity and the attenuation behavior of this mode can be scrutinized. Based on the knowledge gained about the excited modes (speed, attenuation, and coverage), this can be used to develop a sensor network to provide full coverage of the COPV (this is beyond the scope of this work).

Acknowledgments

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