Non-Destructive Evaluation of Plastic Pipeline Cracks

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ABSTRACT

The presence of defects in polyethylene (PE) pipes for natural gas transport can lead to catastrophic failures given the flammable nature of the accident. Third party damage to the external surface of pipeline is among the most common reasons for pipeline failure. In addition, the presence of manufacturing defects on the internal surface of pipeline can result to internal crack growth during pipeline operation. This paper attempts to expand the scope of guided-wave Ultrasonic Testing (UT) to detect both external and internal cracks in a PE pipe, because in its current state, UT is mostly restricted to long range inspection in steel pipes. A laboratory setup is assembled for wave-based monitoring of pipes in controlled damage conditions. The preliminary results demonstrated the potential of UT for detection of both types of cracks, and the findings are used to develop a numerical model which can be later be used to investigate a wide variety of pipeline defects. The outcome of this study establishes the potential of UT to detect both external and internal cracks in PE pipes.

Keywords: Polyethylene pipe; Ultrasonic testing; Guided wave; Crack detection

INTRODUCTION

The use of polyethylene (PE) pipes accounts for most of newly installed natural gas pipelines (Schulte et al. 2006). Therefore, it is crucial to develop new PE pipeline inspection methodologies for effective pipeline maintenance strategies. Despite its advantages of low production cost and high flexibility, PE is a viscoelastic material and is sensitive to operational loads. The development of cracks in the PE pipe, either due to third-party damage, tensile loads, or internal stresses, can reduce its load-bearing capacity, eventually leading to pipeline failure (Harvey 2005). If not detected early, such failures can be fatal, given the flammable nature of natural gas.

A wide range of pipeline tests and models are available to study the impact of cracks on the operational life of the pipeline; however, the same cannot be said for crack detection methods. Hydrostatic strength tests (Palermo et al. 2007) are typically used to predict the service life of the pipeline, and fracture mechanics models (Bouchelarm et al. 2017) are used to study crack growth. In contrast, most crack detection methods are restricted to the welded joint of the pipeline (Hagglund et al. 2012). There is an evident scarcity of studies that focus on detecting cracks in non-welded pipeline regions. This study attempts to address this gap using non-destructive evaluation method for defect detection in pipelines.

Ultrasonic testing (UT) method is widely accepted for the inspection of steel pipelines for a large range of defects such as cracks and corrosion (Ghavamian et al. 2018). The propagation of ultrasonic waves is sensitive to the presence of defects in the material, and defects can be detected by analyzing different wave characteristics, such as the energy of the wave mode. However, its application to PE pipes for crack detection is relatively unexplored. Among the relevant studies, Lowe et al. (2020) attempted to use first-order longitudinal guided wave modes for PE pipe inspection; however, no results were reported for the damaged pipeline. In contrast, Demčenko et al. (2012) and Hong et al. (2017) employed a wave-based inspection for crack detection in polyvinyl chloride pipes using a nonlinear ultrasonic wave modulation technique. They demonstrated the generation of new frequency components due to the presence of cracks and the physical aging of the pipeline.

This study aims to investigate detection of external and internal cracks in PE pipes using guide-wave UT method. Laboratory investigations will be conducted to study wave-crack interaction, and the results will be validated against numerical modeling.

SELECTION OF SIGNAL FREQUENCY

The transmission of waves within a hollow cylindrical structure is governed by the constraints imposed by its boundaries, leading to the generation of three discernible propagation modes: Longitudinal (L), Torsional (T), and Flexural (F). In the Longitudinal mode, predominant displacements are observed along the axial direction of the wall thickness. In contrast, the Torsional mode is characterized by angular displacements, and the Flexural mode involves a complex interplay of radial and angular directions. Each of these modes possesses a distinctive mode shape profile, and their velocities depend on the excitation frequency and the geometric attributes of the structure. The generation of these modes lies across a wide range of excitation frequency spectra, and it is crucial to select the optimal wave modes to ensure their interaction with the defect subject to its size and orientation. This is typically done by studying the wave dispersion profile in the pipeline.

This study is conducted on a medium-density PE pipeline with an external diameter of 220 mm and a wall thickness of 20 mm. Two types of defects will be considered in this study: an external crack of circumferential orientation and an internal crack of axial orientation. The external crack represents third-party damage, whereas the internal defect represents crack growth from pre-existing manufacturing defects. These simpler orientations are chosen for relatively easier fabrication in laboratory conditions.

Table 1. Input parameters for GUIGUW interface

Wave Type	Longitudinal	Shear
Velocity (m/s)	2340 (±2%)	950 (±5%)
Attenuation Parameter (dB/m)	0.055 (±5%)	0.29 (±10%)

A semi-analytical finite element program called GUIGUW was utilized to perform wave dispersion analysis. In Figure 1a and Figure 1c, the energy velocity profiles of various Longitudinal and Torsional modes are depicted. This plot is generated using the material properties outlined in Table 1, as per the previous study (Chan et al. 1998). The anticipated complexity of wave mode generation in the experimental scenario is evident due to the coexistence of different modes right from the beginning of the ultrasonic frequency range. This intricate wave propagation profile is attributed to the lower material density of PE compared to steel. In ultrasonic testing (UT), it is crucial to detect the interaction of specific wave modes in the recorded signals. Therefore, the excitation frequency is chosen at which modes with distinct velocities exist. Moreover, to enhance crack detection resolution, higher frequencies are generally preferred. However, delving into higher frequency domains is challenging due to the complexity of mode generation in PE. Drawing insights from the velocity profile and attenuation profile of wave modes (Figure 1b and 1d), the 4th order Longitudinal mode, i.e., L(0,4), is selected at a frequency of 50 kHz, given the less dispersion, higher propagation velocity, and the lowest attenuation. Using the same logic, the first-order Torsional mode, T(0,1), is also chosen at a frequency of 50 kHz. This results in a mode wavelength of approximately 28 mm and 19 mm for the L(0,4) and T(0,1) modes, respectively.

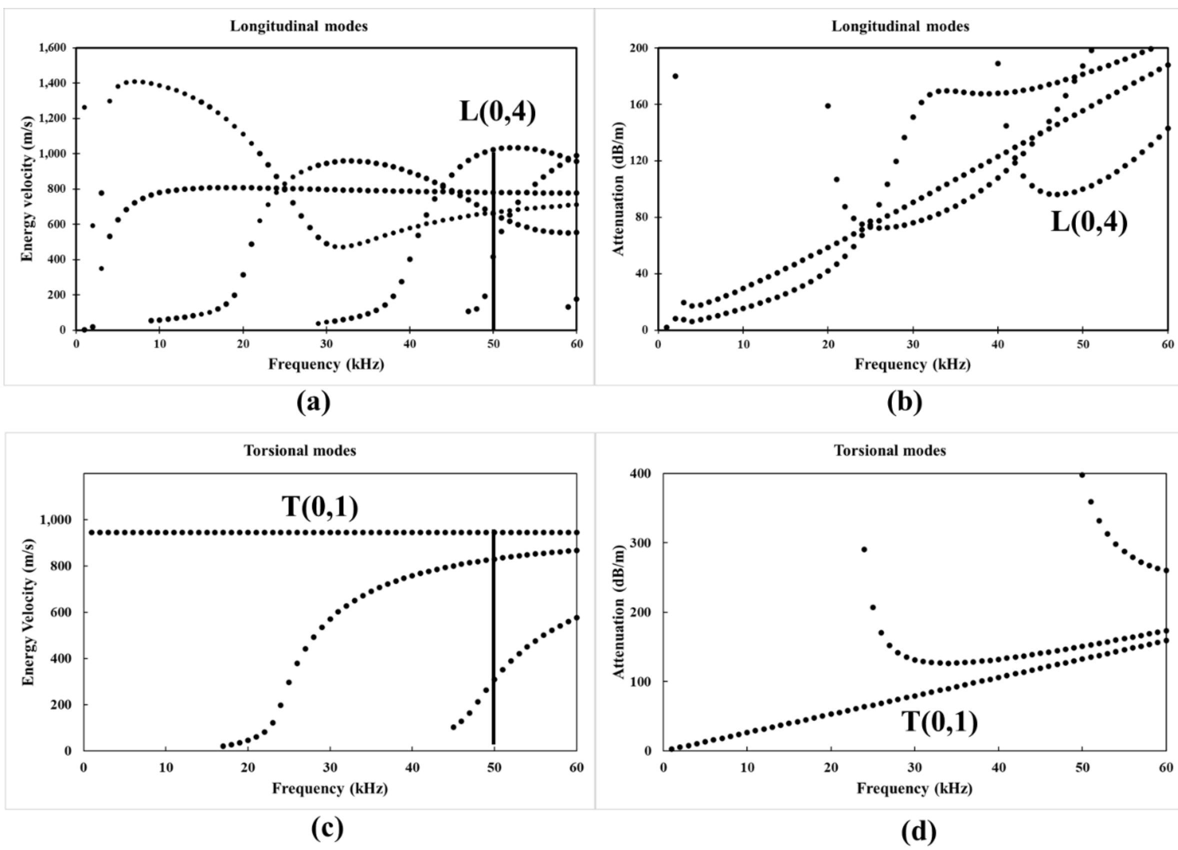

Figure 1. Group velocity profiles of (a) Longitudinal and (c) Torsional mode, and attenuation profiles of (b) Longitudinal and (d) Torsional mode.

EXPERIMENTAL INVESTIGATION

The experimental setup for the planned investigation is illustrated in FIGURE 2. To generate longitudinal modes, piezoceramic patches (PI Ceramics shear c255) measuring 18 mm x 9 mm x 1.76 mm are employed as transmitters and receivers, while patches of dimensions 10 mm x 10 mm x 5 mm are used for the generation and reception of Torsional modes. The distance between the patches is fixed at 200 mm for both types of investigations. To facilitate signal recognition in the transmitted signal, a 5-cycle Hanning windowed signal shape is chosen. For signal generation, a waveform generator is utilized, and the signal is amplified with a power amplifier (E&I 1000S04, Electronics and Innovation Ltd.) before transmission. No amplification is used at the reception end. The transmitted signal is then digitized using an oscilloscope and stored on the PC for later analysis. More details can be found in the authors' previous study (Shah et al. 2023).

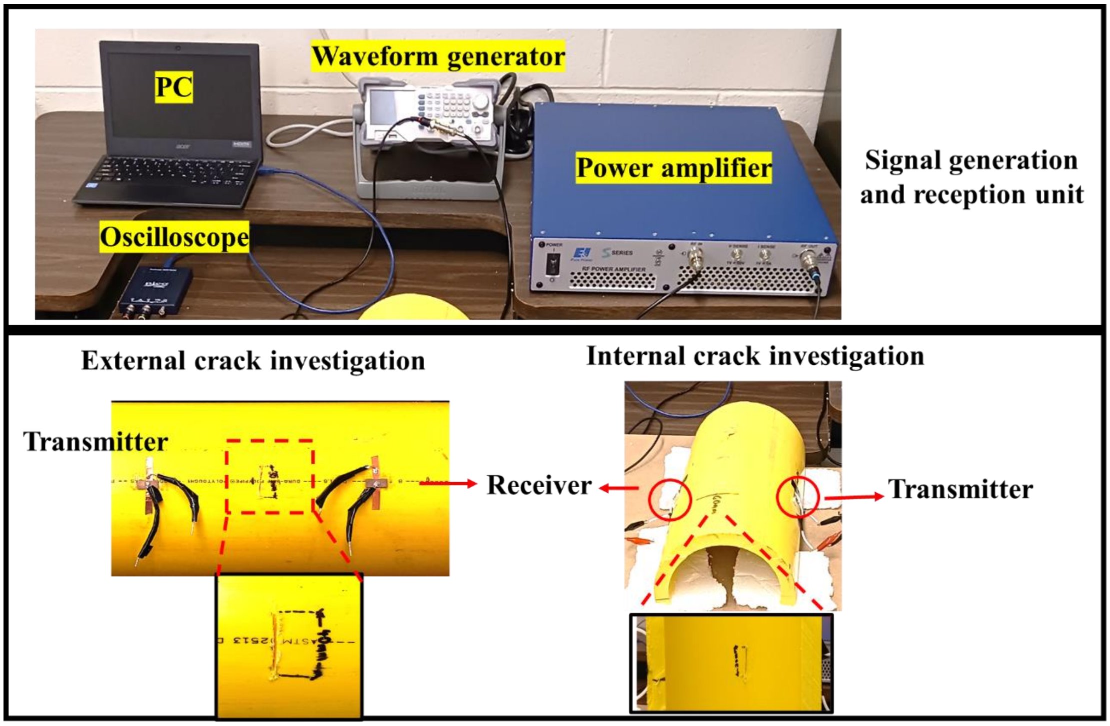

Figure 2. Experimental setup of ultrasonic testing for detection of plastic pipe cracks.

For the external and internal crack investigation, a fixed crack length of 50 mm was chosen, and the crack depth was incrementally increased at every 10% of the wall thickness (2 mm depth) resolution using a handheld power cutting tool. This specific length was selected to ensure that the crack length exceeds the mode wavelength, thereby enhancing the probability of wave-crack interaction.

Figure 3a displays the recorded A-scans for the external crack inspection, where the decay in the strength of the transmitted envelope is observable. It is evident that the first arrived envelope corresponds to the L(0,4) mode, as it is the fastest longitudinal mode with the lowest attenuation at 50 kHz. For signal analysis, the time window from 150 µs to 350 µs is considered. Beyond this time range, other modes traveling at a similar group velocity may be present. The analysis is conducted in the context of signal energy, as shown in Equation 1.

$$E = \sum_{t_i}^{t_f} A(t)^2 \quad (1)$$

Where, E is the transmitted energy of the envelope, A(t) is the recorded amplitude at each time step t, t_i and t_f are the initial and final time bounds of the chosen window.

The energy calculated at each damage state is then presented in decay plots normalized relative to the pristine state of the specimen as shown in Figure 3b. Using a similar analysis approach, Figure 3c shows the interaction of T(0,1) mode and its interaction with the internal crack state, and Figure 3d represents the decay in the transmitted energy at different internal crack stages. For this part of the study, the internal time window of 150 μs to 300 μs was chosen given a relatively similar group velocity of T(0,2) mode that may follow T(0,1) mode as shown in Figure 1c. Given the lowest attenuation of the T(0,1) mode at 50 kHz as per Figure 1d, it can be said with higher confidence that the first transmitted envelope has a higher contribution from the T(0,1). Therefore, from now onwards, all the discussion on internal cracks is presented in the vocabulary of T(0,1) mode.

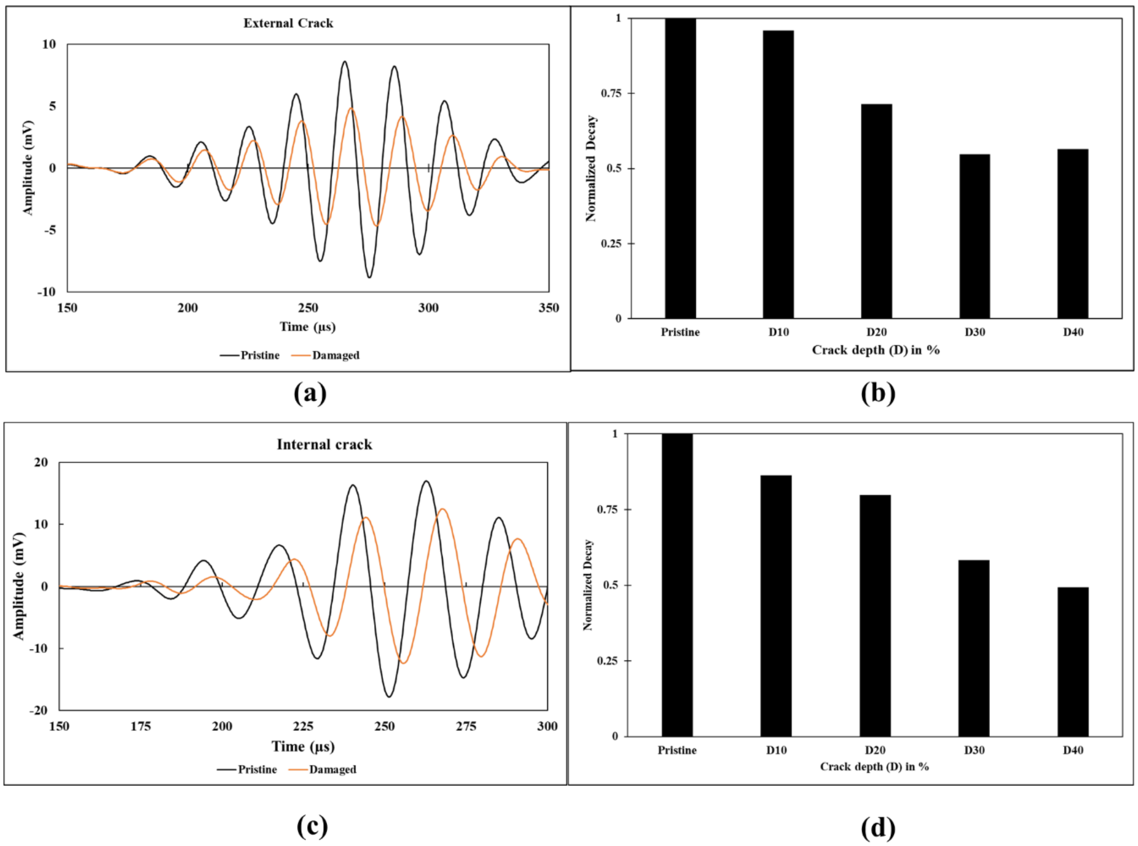

Figure 3. Recorded A-scans for (a) external and (c) internal crack showing decay in the transmitted signal in the presence of crack; Attenuation in the energy of transmitted signal for (b) external and (d) internal crack.

In both investigations, it is evident that as the crack depth increases, there is a higher interaction between the transmitted mode and the fabricated crack. This observation holds true for both internal crack and external crack inspections. Saturation in the transmitted energy is observed at a higher crack depth of 40% in Figure 1b, which may be associated with limited wave-crack interaction at that depth. In contrast, there is a consistent decay in the transmitted energy for the internal crack. These trends may be associated with the mode shape for L(0,4) and T(0,1) modes, as shown in Figure 4. The mode shapes reveal that the L(0,4) mode has relatively low energy associated with the mid-section of the wall thickness compared to the pipe boundaries. On the contrary, the T(0,1) mode offers approximately uniform displacements throughout the wall thickness, making it more sensitive to internal crack growth.

Given the myriad combinations of crack geometries possible in the pipe, conducting experiments for all such cases is not resource efficient. Therefore, a robust numerical model is desired to predict wave-crack interaction efficiently. Hence, the above experimental findings will be utilized to develop a numerical model.

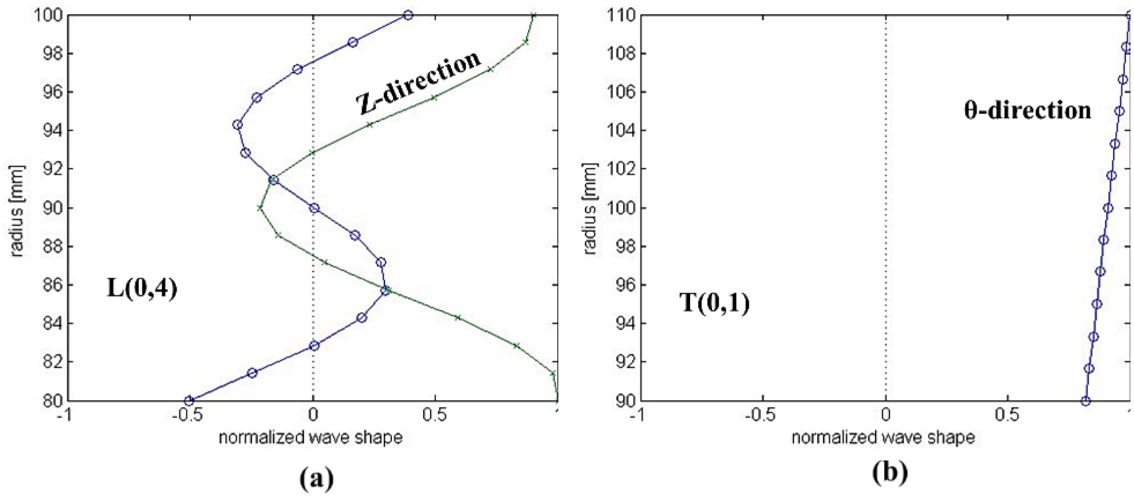

Figure 4. Mode shape of (a) L(0,4) revealing low displacements in the mid-section of the wall thickness, and (b) T(0,1) mode showing approximately uniform displacement through the wall thickness.

NUMERICAL MODELING

A finite element-based numerical model is developed to capture the wave-crack interaction for both external and internal crack scenarios. The model was created using ABAQUS (Smith 2019), a commercial software. Due to the specimen's size and the fine time step requirements for wave propagation, the dynamic explicit solver was employed for modeling wave-crack interaction. To ensure time-efficient simulations, only half of the section is modeled. Since the explicit solver does not support modeling of piezoelectric elements, a shear traction load of 50 kHz with a 5-cycle Hanning windowed shape was applied to the patch dimension area to simulate longitudinal modes, as illustrated in Figure 5a. The transmitted axial displacements were recorded and averaged over the receiver patch area. In contrast, the modeling of the T(0,1) mode in internal crack investigation is done by incorporating its mode shape. This was achieved by applying the ultrasonic load along the wall thickness, consistent with the uniform mode shape along the wall thickness (Figure 4b). The angular displacements were averaged over the receiver patch area to generate A-scans. For crack modeling, mesh elements of the crack geometry were extruded.

To capture the wave dispersion behavior, Rayleigh damping parameters were introduced into the material properties. It should be noted that such properties are not specified in the material datasheet and were selected by testing various values from relevant literature (Gresil et al. 2015, Mehrabi et al. 2022). Similar challenges were encountered in determining other material properties, such as Elastic modulus and Poisson’s ratio, which significantly impacted the simulation accuracy. The only property mentioned in the datasheet was material density. Guided by values found in the literature and a trial-and-error approach, the properties shown in Table 2 were finalized.

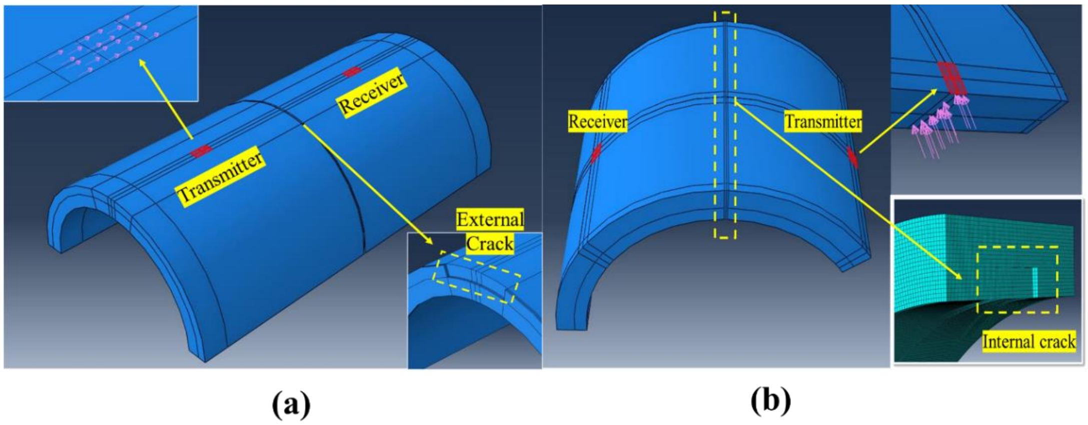

Figure 5. Numerical model for (a) external and (b) internal crack in plastic pipe.

Table 2. Material properties used in numerical models.

Property	Density (kg/m^3)	Poisson's Ratio	Elastic modulus (GPa)	Damping coefficients	
				L(0,4) mode	T(0,1) mode
Values	943	0.39	1.9	$\alpha = 22{,}000$; $\beta = 0$	$\alpha = 0$; $\beta = 4.5e^{-8}$

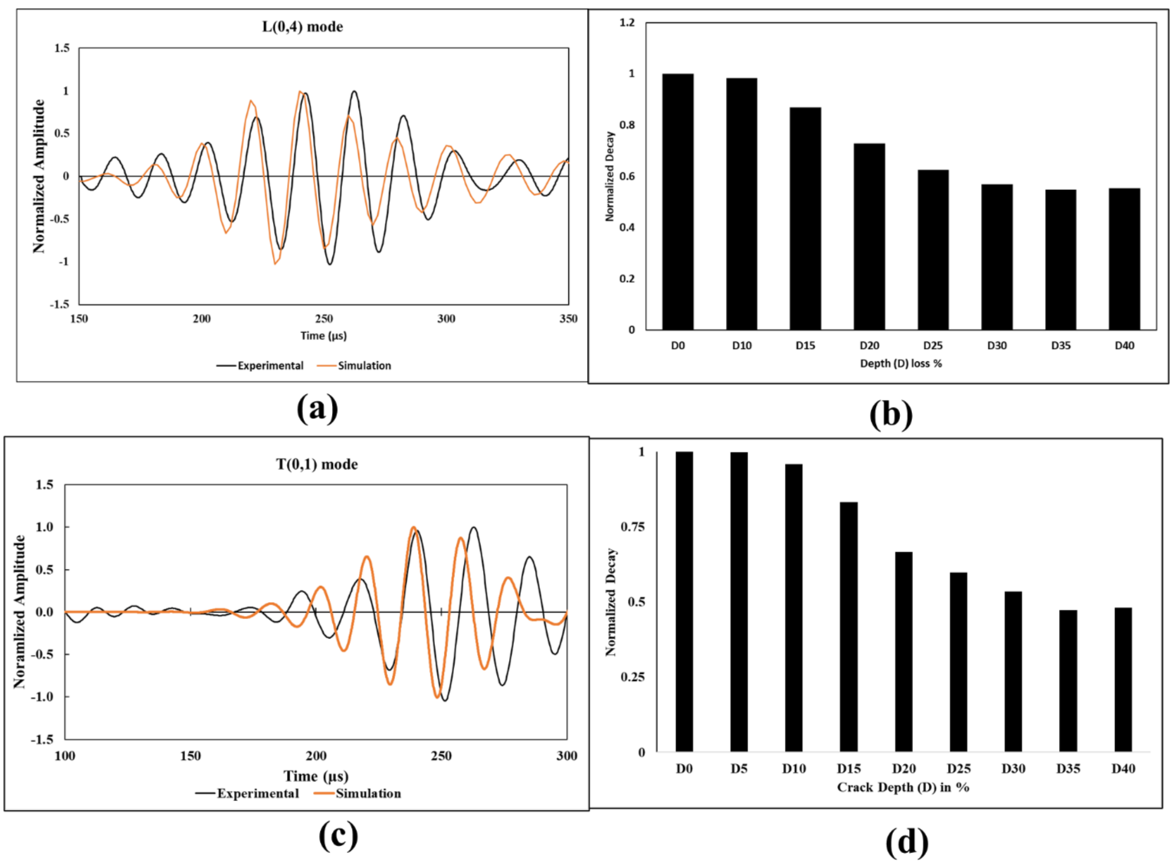

Figure 6. Illustration of normalized (a) amplitude and (b)decay for (a) L(0,4) mode; and normalized (c) amplitude and (d) decay for T(0,1) mode in transmitted energy

Combining these values with the patch modeling approach ensured a match in mode features, including arrival time and signal shape, with the experimental results, as depicted in Figure 6a and 6c. The arrival of L(0,4) and T(0,1) is clearly evident in the simulated signals. Figure 6b illustrates the normalized decay in L(0,4) mode transmission as the crack depth progresses. The simulation results mirror the experimental trend, revealing saturation at higher crack depths. Similarly, the internal crack investigation displays a gradual decay in the transmitted energy of the envelope. Yet, a minor mismatch at initial crack depths compared to experimental observations may stem from the challenge of fabricating precise crack geometries with handheld cutting tools. An acceptable margin of inaccuracy, approximately ±5% or 1 mm in crack depth, can be considered in the analysis. In summary, the numerical model's approach effectively captures experimental observations to a reasonable degree of accuracy.

CONCLUSIONS

This study focused on expanding the application of guided wave UT method to detect external and internal cracks in PE pipeline. The experimental observations were then validated against a numerical model. The main findings of the study are as follows:

- The low-density characteristic of PE results in generation of several co-existing guided wave modes right from the beginning of the ultrasonic frequency range. However, with careful dispersion profile analysis, optimal wave modes travelling at distinct velocities can be selected. For the pipeline used in this study, L(0,4) was used to detect external crack aligned circumferentially and T(0,1) mode was used to detect axially aligned internal crack.
- The wave-crack interaction is subjective to the crack geometry. It is observed that crack lengths greater than the mode wavelength are easily detectible irrespective of their location on the pipe surface.
- The accuracy of the numerical model is sensitive to the material properties of PE, therefore reasonable efforts need to be made to fine tune the material properties considering that the material sheet only provides information on the material density.
- The generation of T(0,1) mode was optimized in the numerical model by incorporating its wave mode shape. In contrast, surface traction approach was used to excite L(0,4) mode.
- Rayleigh damping can be used effectively to capture the dispersive behavior of the wave modes. However, negligible information on these parameters is available in the literature. Therefore, trial and error approach were used in this study to optimize the wave propagation.

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