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Defect detection for polyethylene pipelines based on ultrasonic-guided waves

Yang Liu[1], Huaming Mai[1], Mengfei Cheng[2], Hongzhao Li[2], Weiwei Zhang[1,3] and Rong Lin[1,3,*]

[1]School of Mechanical Engineering, Dongguan University of Technology, Dongguan, 523808, China
[2]School of Mechanics and Construction Engineering, Jinan University, Guangzhou 510632, China
[3]Guangdong Provincial Key Laboratory of Intelligent Disaster Prevention and Emergency Technologies for Urban Lifeline Engineering, Dongguan, 523808, China

[*]Corresponding author's e-mail: linr@dgut.edu.cn

Abstract. The identification of small non-penetrating defects in polyethylene (PE) pipes, utilizing ultrasonic-guided waves, serves as the cornerstone for ensuring the safe operation of these pipes. However, owing to the PE pipe material characteristics, the guided wave has high attenuation in PE pipe, which seriously limits the detection range and accuracy of the guided wave. To address this problem, the dispersion and dissipation characteristics of ultrasonic-guided waves in PE pipes were derived, and the results indicated that the excitation frequency was the important parameter affecting the propagation distance. Then, an experimental platform for PE pipe testing was built using macro fiber composites. The acoustic attenuation coefficient and dispersion were calculated. After considering the effects of dissipation and dispersion on the guided wave, the optimal excitation frequency was selected to extend the guided wave detection distance to 4 m. Finally, an experimental study on ultrasonic-guided wave detection of defects in PE pipes was conducted. The experimental results showed that non-penetrating small defects with a section loss rate of 8% could be effectively identified and located using ultrasonic-guided waves.

1. Introduction

PE pipelines have strong adaptability to harsh service environments and are widely used for long-distance transport of oil and gas[1]. The identification of small non-penetrating defects in polyethylene (PE) pipes is the basis for the safe operation of PE pipes. At present, the commonly used pipeline detection methods include pressure detection and infrared imaging[2]. However, these methods can only identify penetration defects in PE pipes but cannot be effective in identifying non-penetrating small defects.

Ultrasonic-guided wave detection technology is widely used for damage detection of slender structures such as pipelines and anchor rods[3]. It has the advantages of a large detection range and high accuracy, which provides a new method for defect detection of PE pipelines. Many scholars have conducted research on PE pipeline detection based on ultrasonic-guided waves. For example, Song et al. [4] analyzed the effects of the number of piezoelectric sheets and excitation gain multiples on the propagation characteristics of guided waves in PVC pipes. The experimental results indicated that there is no significant correlation between the piezoelectric sheets and propagation distance guided waves. Shahj et al. [5] investigated the influence of crack geometry on the amplitude of guided waves in PE pipelines. The defect identification effect of guided waves with different frequencies and orders was analyzed, which provides a basis for the selection of guided wave modes. Lowe et al. [6] used macro fiber composites as the ultrasonic transducer to excite ultrasonic-guided waves in PE pipes. Experiment results showed that low-frequency guided wave signals had a longer propagation distance.

Although the above studies have been fruitful in using ultrasonic-guided waves to detect PE pipes, there are two intractable problems. On the one hand, PE pipes are made of viscoelastic materials [7], which results in a high degree of attenuation of ultrasonic-guided waves in PE pipes. On the other hand, the guided wave in the PE pipe excited by the existing ultrasonic transducer had a low energy. To address these two problems, a defect detection method for PE pipes based on ultrasonic-guided waves was proposed by combining theoretical derivation and experimental study.

2. The propagation characteristic of ultrasonic-guided waves

Considering that PE pipes are viscoelastic materials, the viscoelastic constitutive is characterized using the classic Kelvin-Voith model as follows:

$$\sigma = E\varepsilon + \eta\dot{\varepsilon} \tag{1}$$

where E denotes Young's modulus and η denotes viscosity coefficient. Substituting the Eq. (1) into a one-dimensional wave equation yields the following expression:

$$u_{tt} - c_0^2 u_{xx} - \eta u_{xxt} = 0 \tag{2}$$

where u denotes displacement, ρ denotes density, and c_0 denotes wave velocity. Let $u = Ae^{i(kx-\omega t)}$, and substitute it into Eq. (2). The wave number *k* can be obtained as follows:

$$k^2 = \frac{\omega^2}{c_0^2 - i\eta\omega} \tag{3}$$

By substituting Eq. (3) into the $u = Ae^{i(kx-\omega t)}$, u can be obtained as follows:

$$u = Ae^{-ax}e^{i(bx-\omega t)} \quad a = a(\omega) \quad b = b(\omega) \tag{4}$$

where Ae^{-ax} is the amplitude. It can be seen from Eq. (4) that amplitude decreases as a increases, which reflects the dissipation of guided waves during propagation. On the other hand, wave number is *a* function of frequency, which indicates the existence of dispersion in guided waves. Owing to the fact that a and *b* are functions of frequency, the dispersion and dissipation of guided waves are both affected by frequency. In summary, the selection of an optimal excitation frequency is the key to reducing guided wave attenuation and increasing the propagation distance. To address this problem, we conducted an experimental study on the propagation of ultrasonic-guided waves in PE pipes.

3. Experimental study

3.1. Experimental setup

The experimental setup for ultrasonic-guided wave detection of PE pipelines is shown in Figure 1. PE pipe with an external diameter of 75mm, wall thickness of 4.5mm, and length of 2m was placed on two wooden plinths to protect them from the environment. The excitation transducers used MFC2814-P1 macro fiber composites with a length of 28mm and a width of 14mm. 8 MFC were arranged equidistantly at the end of the pipe for excitation of guided wave signals into the pipe. A total of 16 piezoelectric sheets that are 15 mm long and 3 mm wide were used as sensors to receive signals.

A Tektronix AFG3022 arbitrary function generator was used to generate a modulated waveform signal that was fed into a Tegam 2350 dual-channel power amplifier. The electrical pulse signal was amplified by a power amplifier and was transmitted to the MFC to generate a mechanical wave signal. Finally, piezoelectric sheets were used to receive signals. The Tektronix TDS3000C high-performance digital oscilloscope was used to monitor and analyze the guided wave propagation process. The L (0,2)

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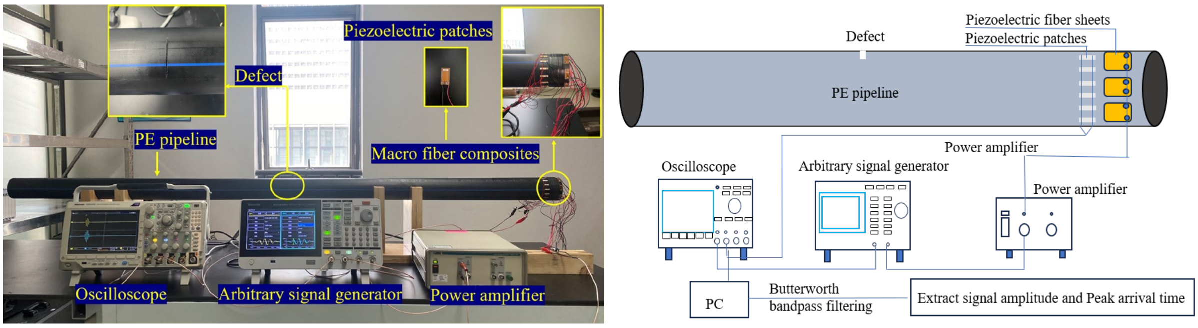
mode with fast wave speed and concentrated energy is selected as the detection signal for PE pipes. The sampling frequency is 25kHz.



(a) (b)

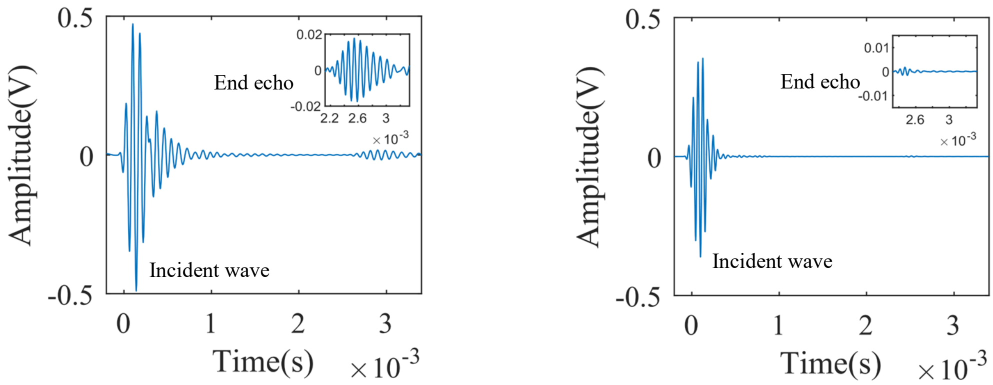
Figure 1. Experiment on a PE pipeline using ultrasonic-guided waves: (a) Experimental setup; (b) Experimental principles.

3.2. Experimental results and analysis of dispersion and attenuation of ultrasonic-guided waves

The excitation frequency increased from 8kHz to 25kHz with a step size of 1kHz, and guided wave signals were collected. According to Eq. (5), the average attenuation coefficient at different frequencies can be calculated using the amplitude of the incident wave and the end echo.

$$\alpha = \frac{20\lg\left(A_1 / A_2\right)}{s} \tag{5}$$

where A_1 and A_2 are the amplitude of the incident wave and the end echo, s is the propagation distance and α is the average attenuation coefficient. Figure 2(a) is a guided wave at 12kHz, and the end echo is clearly visible. The amplitude of the end echo is approximately 0.02. Figure 2(b) is a guided wave at 18kHz, and the amplitude of the end echo is approximately 0.007. The amplitude of the end echo decreases with increasing frequency. To obtain the relationship between attenuation coefficient and frequency, the average attenuation coefficient of guided waves was calculated from 8kHz to 25kHz, and the results are shown in Figure 3(a).



(a) (b)

Figure 2. Guided wave signals at different frequencies: (a) 12 kHz; (b) 18 kHz.

Obviously, when the detection frequency is less than 12 kHz, the attenuation coefficient rises with decreasing frequency. In the interval from 12 kHz to 25 kHz, the attenuation coefficient elevates as the guided wave frequency increases. The guided wave with a frequency of 12 kHz has the smallest attenuation coefficient. However, since the dispersion affects the wave packet integrity of the guided wave, dispersion characteristics also need to be considered when selecting the frequency. Therefore, it is necessary to analyze the dispersion of the guided wave in the PE pipe.

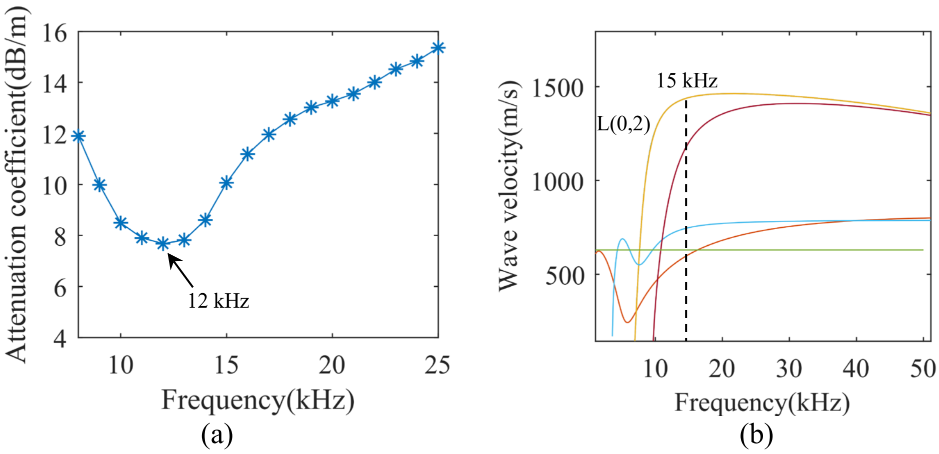


Figure 3. The propagation characteristics of ultrasonic-guided waves. (a) Attenuation curve. (b) Dispersion curve.

The DISPERSE developed by the Imperial University of Technology was used to draw the dispersion curve of PE pipes, as shown in Figure 3 (b). The wave velocity corresponding to 12 kHz is at the inflection point of the L (0,2) modal curve. The wave velocity at 12 kHz varies greatly with frequency and exhibits severe dispersion. In the frequency range greater than 15kHz, the guided wave velocity tends to stabilize. Owing to the attenuation of the guided wave increases with increasing frequency, the minimum frequency of 15 kHz at which the wave speed is stable is chosen as the optimum frequency.

4. Defect detection for PE pipe

4.1. Defective manufacturing

To investigate the feasibility of ultrasonic-guided wave detection of defects in PE pipes, an experimental study of ultrasonic-guided wave detection of defects in PE pipes was conducted. Cracks were created in the PE pipe at a distance of 1 m from the excited end. By keeping the radial size of the cracks constant and gradually increasing the circumferential size of the cracks, different degrees of pipeline damage conditions can be obtained. Here, the sectional loss rate is used to measure the degree of defects, and four experimental conditions were set up and the defect parameters for each condition are listed in Table 1. Herein, β is the sectional loss rate, l is the circumferential size, h is the depth of the defect, and D and d are the inner diameter and outer diameter of the PE pipeline, respectively.

Table 1. Conditions for PE pipe.

Defect parameters	Condition 1	Condition 2	Condition 3	Condition 4
Sectional loss rate β/%	-	8	10	12
Circumferential size l/mm	-	43.50	54.38	65.26
Defect depth h/mm	-		2	

4.2. Defect detection

To improve the accuracy of defect recognition, Butterworth bandpass filtering is used to denoise the received signal [8]. To avoid signal distortion, the upper and lower cut-off frequencies are set to 20kHz and 10kHz, respectively. The experimental signals after noise reduction are shown in Figure 4. The experimental signal of the intact pipeline only contains the incident wave and end echo, while there is no defect echo, as shown in Figure 4 (a). A defect echo can be observed in Figure 4(b), indicating that the pipeline in Condition 2 contains a defect. Condition 3 and Condition 4 are similar to Condition 2, and defect echoes can be observed in Figure 4(c) and Figure 4(d). In addition, the amplitude of the defect echoes gradually increases as the defect size increases.

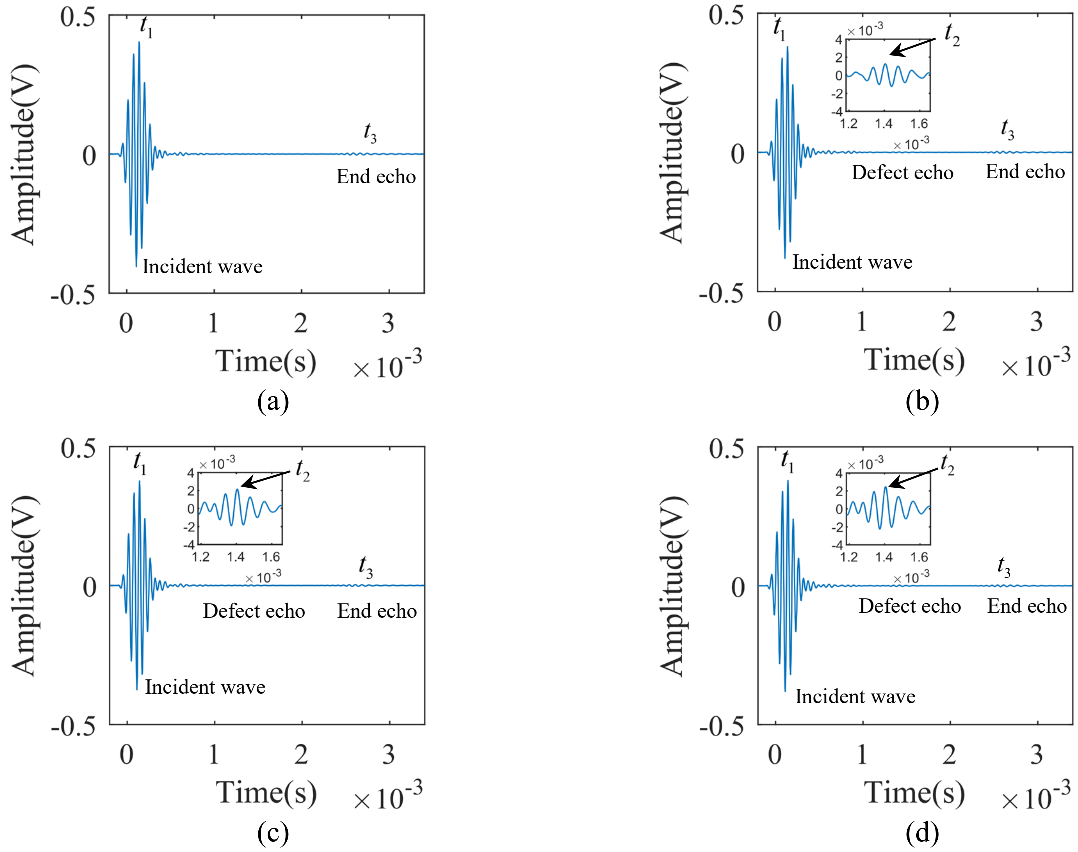


Figure 4. Experimental signals under different conditions: (a) Condition 1; (b) Condition 2; (c) Condition 3; (d) Condition 4.

From Figure 4, the peak arrival times of the incident wave, defect echo, and end echo can be obtained, which are defined as t_1, t_2, and t_3, respectively. The defect location s_x can be obtained using the following equation.

$$s_x = \frac{t_2 - t_1}{t_3 - t_1} L \tag{6}$$

where L is the pipe length. By substituting t_1, t_2, and t_3 for each condition into Eq. (6), the defect location can be calculated, and the results are shown in Table 2. Obviously, as the defect size increases, the relative error of defect location decreases. The maximum relative error in location identification for Condition 2 is 6.6%, which indicates that the proposed method can effectively identify the location of defects in PE pipes. The detection distance of guided wave for existing relevant studies [5, 6] had a of 0.9 m and could identify minimum defects of sectional loss rate of 10%. In this paper, the detection distance was extended to 2 m, and small defects with a section loss rate of 8% can be identified.

Table 2. Defect location detection results.

Condition No.	t_1/s	t_2/s	t_3/s	s_x/m	Location identification error/%
2	7.558886e-7	0.001354	0.002541	1.066	6.6
3	5.344468e-7	0.001321	0.002536	1.042	4.2
4	2.539732e-7	0.001274	0.002469	1.031	3.1

5. Conclusions

To address the problems of large attenuation and short propagation distance of ultrasonic-guided waves in PE pipes, a guided wave detection method for PE pipes combining theoretical and experimental research was proposed. Firstly, the effect of frequency on guided wave dissipation and dispersion was analyzed from the theoretical level. Then, macro fiber composites were selected as excitation sensors, and the optimum detection frequency of the guided wave was determined. Finally, an experimental study of ultrasonic-guided wave detection of defects in PE pipes was carried out, and the location of small defects was successfully identified. Some conclusions are summarized as follows.

(1) The wave equation of the PE pipeline was established using the viscoelasticity constitutive relationship. The results indicated that frequency was an important factor affecting the propagation distance of guided waves in PE pipes.

(2) The macro fibre composites can excite higher energy in the pipe and is suitable as an excitation transducer for ultrasonic inspection of PE pipes. By analyzing the dispersion and attenuation of the guided wave, the optimum excitation frequency of 15 kHz was determined.

(3) Experimental studies demonstrated that ultrasonic-guided waves can detect small, non-penetrating defects in PE pipes. We successfully identified defect location with a sectional loss rate of 8% in a 2-meter PE pipe, which provides a basis for ultrasonic-guided wave detection of defects in PE pipes.

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