The Energy Distribution Properties of the Guided Wave in the Underground Layered Pipeline Structure: Finite Element Simulation and Experimental Verification

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Abstract. Many layered pipe structures (LPSs) are covered under the soil, so it is important to investigate the guided wave propagation characteristics for underground LPSs in structural health monitoring (SHM). The paper aims to propose a finite element model to describe the ultrasonic guided wave propagation properties in (underground) layered pipeline. Firstly, a selection of suitable excitation frequency and mode of PZT-based guided waves is successfully finished. Secondly, finite element analysis (FEA) using ABAQUS software is applied to establish an (underground) layered pipe model with piezoceramic (PZT) transducers for generating the guided waves. The finite element analysis (FEA) results show that the soil have a significant impact on the generating modes. The analysis of reflection signal is difficult because of mode conversion. Thus, the energy method of guided wave is used in order to analyze properties of underground layer pipe. The soil impacts for layered pipe focus on the axial energy properties. Although a part of guided wave energy scatters into pipe layers even the soil which makes the behaviour description much more complicated, the remained guided wave energy is still sufficient enough for propagating in the pipe with the obvious frequency dispersion and mode conversion. An experimental system is established to verify the mentioned research, and the experimental and numerical results match well.

1. Introduction

It is a feasible method to detect the pipe structure using ultrasonic guided wave. In daily applications, most of the layered pipe structures are buried below the soil. Due to the complex geometric and material properties but also the influence of being covered by soil, it is difficult to implement the structure health monitoring (SHM) for the layered pipeline structure. In this paper, the energy distribution properties of guided waves in various layered structures are simulated by finite element
method (FEM). The energy values of guided waves in each layered structure and the soil structure is calculated by the energy method, and the mechanism of guided wave energy distribution is studied.

2. Finite element simulations

2.1. Choice of excitation signal

The study of the three layered pipeline structure is rarely reported, while the three layer pipeline structure is widely used in the basic construction. A typical three layered pipe structure is polyurethane insulation pipe, which is composed of steel material (inner structural layer), rigid polyurethane foam (RPF) material (intermediate thermal insulation layer) and high density polyethylene (HDPE) material (outer anti-corrosion layer). That structure is widely used in municipal heating engineering, oil and gas transportation engineering. The geometric and physical properties of the three layered pipe structure and soil property are shown in Table 1 as follows:

| Parameters | Radius (mm) | Thickness (mm) | Longitudinal wave velocity (m s\(^{-1}\)) | Poisson's ratio (Gpa) | Density (kg m\(^{-3}\)) |
|------------|-------------|----------------|------------------------------------------|----------------------|-------------------------|
| steel      | 34          | 4              | 5172                                     | 0.3                  | 7850                    |
| RPF        | 38          | 30             | 3122                                     | 0.25                 | 80                      |
| HDPE       | 68          | 2              | 763                                      | 0.45                 | 946                     |
| soil       | 70          | 1000           | 141                                      | 0.35                 | 2000                    |

The depth of the layered pipeline structure in the soil has a certain influence on the guided wave propagation properties. When that depth is 1000mm, the dispersion curves of the guided wave in the layered pipe structure are shown in Figure 1 (b). For the geometrical and physical properties of Table 1, there are 11 kinds of \(L\) modes of ultrasonic guided waves in the underground layered pipe structure, which are greater than 8 kinds of modes in the layered pipe structure without soil, as shown in Figure 1(a). In the frequency range of 70 to 90kHz, the group velocity of \(L\) (0,9) mode guided wave that is non-dispersive is higher than the other modes, so it is suitable for SHM of the layered pipeline structure with the soil depth of 1000mm. However, the large number of guided wave modes in that frequency domain, it is difficult to excite the single \(L\) (0,9) mode. If the kinds of modal of the excitation guided waves are numerous, the analysis echo method cannot be used to analyze the guided wave property. Therefore, the energy distribution method is used to study the propagation properties of the guided wave in the structure. Combined with the mentioned research, the 5 peak wave with a central frequency of 80 kHz modulated by the Hanning window function is used as an excitation signal with 5V amplitude.\(^{[1,2]}\)

![Figure 1. Group velocity dispersion curve.](image)
2.2. The establishment of the finite element model of underground layered pipeline structure

2.2.1. Establishment the layered pipeline structure model.
In the Part module, a piezoelectric model (PZT) with the same geometric properties is established with a size of $12 \times 6 \times 1$ mm in ABAQUS software. In the Property module, the properties of the material and the piezoelectric characteristics are defined, and the direction of piezoelectric element thickness (d33) is defined as the polarization direction[3]. Three layers pipeline structure model that geometric properties and material properties are shown in Table 1 is established. The three layers and the piezoelectric unit component are assembled in the Assembly module. In the circumferential position of pipeline structure at the end of 30mm position, 16 PZT patches are arranged as actuators, and 4 PZT patches are arranged with the same end of 300mm in the same pipeline structure, as seen in Figure 2.

![Figure 2. Finite element method mesh diagram.](image1)

![Figure 3. Finite element model of underground multi-layer pipeline structure.](image2)

2.2.2. Establishment underground layered pipeline model.
The soil property is shown in Table 2, and the soil depth (the soil surface to the bottom of the pipe structure) is 1000mm. Because the further distance between the soil and the pipe axis is, the less influence of soil to guided wave propagation in the structure is. In order to save computation cost, the soil is meshed two parts: one grid size is 20mm that distance from pipeline’s axis in the range of 0.2m (the red range in Figure 3), and the other grid size is 50mm (blue range in Figure 3). The pipe structure is connected to the soil structure by Tie.

![Figure 2. Finite element method mesh diagram.](image1)

![Figure 3. Finite element model of underground multi-layer pipeline structure.](image2)

2.3. Results analysis of finite element simulation

2.3.1. Analysis of radial propagation properties.
The energy change of the ultrasonic guided wave in the radial section is studied, that is, the energy percentage of the ultrasonic guided waves in each layers structure of the whole structure. Due to the axisymmetric structure, the calculation method is simplified in this paper. The energy values of nodes at different radial locations in the section are calculated instead of element energy values. The section energy value is the sum of nodes energy values at different radial locations. The energy calculation method is the nodal displacement method

$$E_i = \sum_{t=0}^{n_1} (x_i(t))^2$$

where $x_i(t)$ is the guided wave node displacement in the $t$ time domain.

The radial section of $Z=1$m axial position is selected to study the radial propagation properties of ultrasonic guided waves in the underground layered pipeline structure. The grid size is taken as the
step length to calculate the node energy value, and then the energy values of different nodes in the section are added together, then the total energy value of the layered pipe structure is obtained. The calculation results show that the amplitude of ultrasonic guided wave decreases obviously because of guided wave transmission from layered pipe to the soil, and based on Formula (1), it is known that the energy of the guided wave of the layered pipe structure accounts for 99.7% of the total energy, while the energy leakage to the soil accounts for 0.3% of the total energy.

2.3.2. Analysis of axial propagation properties.
In order to separate the echo from the initial wave, the 4 received PZT patches are set at the Z=300mm position. The guided wave propagation process in the structure is shown in Figure 4. The propagation mechanism of the guided wave in the pipe structure indicates clearly in Figure 4 (b). In addition to boundary echo signal, it is obvious that there are mode conversion guided waves, that is, in the black solid line of Figure 4 (a). It can be seen in the Figure 4 that guided waves propagate in the underground layered pipeline structure, the amplitude decrease with the propagation distance and the end reflection, and the pulse width of guided wave guided will increase with the increase of propagation. This indicates that the guided waves modes are affected by the soil in order to serious mode conversion, and there may be some interface reflection and refraction. This conclusion is agreed with the mentioned conclusion in Figure 1.

![Figure 4. Results Analysis of finite element simulation.](image)

(a) the waveform of the sensing signal. (b) transmission mechanism of sensing signal

The FEM advantage is that it can not only analyze the guided wave signal in the reception element, but also analyze guided wave propagation properties in each position. Three axial positions of underground layered pipeline structure are selected to analyze the guided wave propagation properties with the energy distribution method, as shown in Figure 5. Compared with the waveforms before being covered with soil, the guided waves amplitude after being covered with soil decreases obviously, and the reason is serious energy attenuation of guided wave. In the time domain, the first boundary reflection signal (the yellow solid line) that reflected by the other end (no actuation end) is chosen as the subject in the Figure 4 (a). In the Figure 5 (a), (b) and (c) indicate that the reflection signal amplitude after being covered soil is reduced to 9.86%, 47.44% and 69.54%, respectively. Due to the energy attenuation caused by energy leakage, the guided waves propagation velocity in the underground layered pipeline decreases, and the declined time of the first boundary reflection signal amplitude is 10 μs, 29 μs and 52 μs, respectively. Meanwhile, the mode conversion is obvious in figure 5 (a) than (b) and (c), because there are many guided wave modes in the actuation early domain. Due to close to the actuation position, the energy attenuation is less, and the displacement amplitude does not decline much in order to the propagation velocity decrease to a minimum, in figure 5(a). By contrast, with the larger propagation distance, the guided wave energy attenuation in the propagation process is more serious, so the propagation velocity and displacement amplitude decreases seriously in figure 5 (b) and (c).
The guided waves propagation in the underground layered pipeline structure has caused serious mode conversion and energy attenuation, in order to amplitude decrease of boundary echo signal with the propagation distance increasing, and it is more and more difficult to distinguish boundary echo signal from mode conversion. Therefore, the concept of energy ratio is introduced to evaluate the guided waves propagation properties in pipeline structures after being covered soil. The equation [4] is:

$$ R = \frac{E_u}{E_o} $$

where $E_u = \sum_{t=0}^{t_2} (x(t))^2$ and $E_o = \sum_{t=0}^{t_2} (x(t))^2$, is reception guided wave energy with and without being covered by soil, respectively.

![Graph showing displacement and time for different positions](image)

Figure 5. Compare of periodic waveform in FEM.

The piezoelectric signal is received at the axial pipe position at $Z=0.3m$, and displacement signals are received at the axial pipe position at $Z=0.5m$, $Z=1.0m$ and $Z=1.7m$. Then, the energy and energy ratios are calculated by the equation (2). At the positions of 0.3m, 0.5m, 1.0m and 1.7m, the energy value decreased by 91.27%, 76.27%, 69.55% and 43.34%, respectively, after pipe structure being covered by soil. It is mentioned that the soil effect on the guided waves propagation properties in the structure is obvious, and it is verified indirectly that energy can leak from pipeline structure to the soil, but the leakage energy cannot return to pipeline structure. With the distance increasing from the reception position to the actuation position, the guided wave energy value decreases more serious, and this means that the energy ratio decreases. It indicates that the longer the propagation distance is, the more serious the attenuation of the guided wave is.

3. Experimental verification

Based on the pulse echo principle, two experimental systems are set up to verify group velocity and energy distribution properties. One is laboratory experimental system, and the other is the actual
experimental system. The ultrasonic guided wave propagation in (underground) layered pipe structure is detected, respectively, and then the energy ratio is calculated. The energy ratio of experimental energy ratio is compared to FEM’s energy ratio to verify the consistency. The results can be seen in Figure 6 that experimental energy ratio is slightly smaller than the finite element simulation value. However, with the axial propagation distance increasing, the trend of decreasing energy ratios is the same. Therefore, experiments confirm that the energy attenuation of guided wave propagation in the (underground)layered pipeline is agreement with FEM, and the longer the axial distance from the excitation location is, the more serious the energy value decreases.

![Energy ratio comparison diagram (FEM and experiment).](image)

4. Conclusions
According to the analysis of dispersion curves, FEM and experiment, the following conclusions are obtained:

The FEM shows that the guided waves radial propagation properties: a part of energy of guided wave propagation leak into the soil, but the proportion which is only 0.3% of total energy value. With the radial distance increasing, the energy value reduces obviously.

The guided wave axial propagation properties: the guided wave amplitude decreases obviously that indicated energy attenuation is serious in order to the propagation velocity is reduced. Energy attenuation is caused by leakage, and the leakage is unidirectional. The obvious mode conversion increases the difficulty of SHM. Therefore, the energy ratio equation is proposed to describe guided wave properties in the underground layered pipeline, which the farther the propagation distance is, the more serious the attenuation of the guided wave energy is.

The experiment results show that the guided wave energy attention is more serious than the FEM. However, that difference is seldom obvious, and verifies the feasibility using energy distribution to analyze guided wave propagation properties in underground layered pipeline.

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