Numerical Simulation of Liquid Level Detection in Zirconium Alloy Pipes through Flexural Mode of Ultrasonic Guided Waves

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Abstract: *Accurate liquid level monitoring in zirconium alloy pipes remains challenging due to the limited sensitivity of conventional axisymmetric guided wave modes to the asymmetric mass loading induced by partial liquid filling. In this study, a nondestructive evaluation strategy exploiting the F(1,1) flexural mode is proposed, and the non-axisymmetric displacement field offers enhanced sensitivity to the presence of local liquid. Through dispersion analysis, the differences in the dispersive characteristics of the F(1,1) flexural mode between water-filled and empty zirconium alloy pipes are calculated and validated. By acquiring full-wavefield information on the outer pipe wall, we employ frequency–wavenumber analysis to identify the effectively excited F(1,1) flexural mode and to extract the wave velocity shift and signal attenuation features correlated with liquid level. Using excitation and receiving sensors placed on the outer pipe wall, the liquid level is identified through the changes in guided wave propagation caused by liquid loading. The results show that variations in liquid level induce a time delay and attenuation of the guided wave, and that the time-of-flight difference exhibits a highly linear relationship with liquid height. This method enables high-precision liquid level monitoring without intruding into the pipe interior, providing a feasible technical approach for industrial pipeline condition monitoring.*

Keywords: *Frequency-wavenumber analysis; zirconium alloy tube; F(1,1) mode; liquid level detection*

1. Introduction

Zirconium alloy pipelines exhibit high tensile strength, exceptional corrosion resistance, and good thermal conductivity, serving as critical components in energy, chemical, nuclear, and hydraulic infrastructure [1]. Anomalous liquid-level fluctuations in multiphase flow systems often foreshadow catastrophic failures including leaks and explosions [2]. Consequently, developing non-invasive, high-precision liquid level monitoring technologies is essential for safeguarding critical infrastructure reliability.

Ultrasonic guided wave technology has garnered considerable attention in structural health monitoring owing to its single-ended excitation capability, long-range propagation, and sensitivity to cross-sectional changes. In liquid-filled pipes, fluid-structure coupling significantly alters wave propagation dynamics. Previous liquid-level measurement approaches include that of Liu et al. [3], who proposed a separated electromagnetic acoustic sensor system that estimates levels via surface-wave time-of-flight differences, and the technique of Shi et al. [4], which employs electromagnetic acoustic resonance utilizing long-pulse excitation to induce wall resonance without medium contact. While these studies provide valuable insights, they predominantly rely on axisymmetric modes or bulk wave methods, which exhibit limited sensitivity to the asymmetric loading induced by partial filling.

Flexural modes, characterized by non-axisymmetric displacement fields, demonstrate heightened sensitivity to asymmetric mass loading from partial liquid containment. However, their excitation and detection present considerable challenges, as conventional piezoelectric transducers suffer from adhesive degradation and poor high-temperature tolerance. Non-contact measurement methodologies offer distinct advantages. Lucklum et al. [5] demonstrated that electromagnetic acoustic resonators eliminate adhesive requirements, permit millimeter-scale lift-off distances, and deliver superior signal-to-noise ratios. Tian et al. [6] employed scanning laser Doppler vibrometry to excite and receive guided waves in water-filled pipes, achieving quantitative gas accumulation detection through frequency -wavenumber analysis while validating the linear relationship between liquid level and wave propagation time.

Consequently, a pipeline liquid level detection method exploiting the liquid level guided wave coupling effect is developed based on flexural-mode ultrasonic guided waves. First, we calculate and validate the dispersion curves of the zirconium alloy pipe under liquid-filled and empty conditions using COMSOL Multiphysics modal analysis and Disperse software, thereby clarifying the differences in the dispersive characteristics of the F(1,1) flexural mode between these two states. Subsequently, full time-domain datasets are acquired through finite element simulations, and frequency–wavenumber analysis is employed to extract wavenumber-domain features [7], which reveals the propagation delay response of the F(1,1) flexural mode under liquid-filled and empty conditions. Finally, simulation experiments are conducted using a pitch-catch sensor configuration mounted on the outer wall of the zirconium alloy pipe, and a quantitative mapping relationship between guided wave characteristic parameters and liquid-level height is established, which provides a feasible technical solution for high-precision pipeline condition monitoring in complex industrial environments.

2. Simulation Design Validation

2.1. Analysis of Guided Wave Propagation Characteristics in Pipelines

This paper investigates Zr705 zirconium alloy pipes, which are isotropic media; the specific material parameters and geometric dimensions are shown in Table 1. To characterize guided wave propagation, we compute dispersion curves using the modal analysis module of COMSOL Multiphysics and validate these against Disperse software (Fig. 1). Figures 1a and 1b compare the frequency-wavenumber relationships for empty and water-filled pipes, respectively, across 0–400 kHz. The strong agreement between both computational approaches confirms pronounced multimodal characteristics within this frequency range. Most modes exhibit non-zero cutoff frequencies, with modal density increasing approximately linearly with frequency, which promotes modal aliasing and complicates signal interpretation. Crucially, validation reveals distinct dispersive properties for the F(1,1) flexural mode under liquid-filled versus empty conditions: the wavenumber curve shifts to higher values upon filling, indicating modified group velocities that provide the theoretical foundation for distinguishing propagation regimes. Consequently, we restrict excitation frequencies to the low-frequency regime to ensure unambiguous modal identification in subsequent simulations and experiments.

Table 1 Material properties

Parameter	Value
Density $\rho/(kg \cdot m^{-3})$	6640
Young's modulus E/Pa	94.7×10^9
Poisson's ratio υ	0.33
Pipe diameter D/mm	9.17
Pipe wall thickness d/mm	0.76
Speed of sound in water $v/(m \cdot s^{-1})$	1500

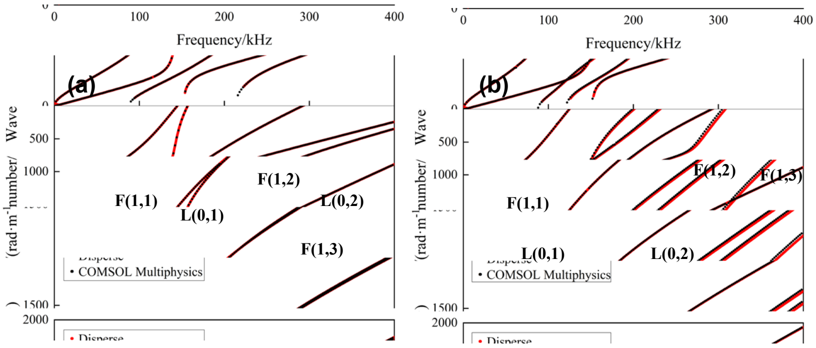

Figure 1 Comparison of dispersion curves for hollow and fluid-filled Zr705 pipes obtained using Disperse and COMSOL Multiphysics. (a) Hollow pipes; (b) Fluid-filled pipes.

2.2. Numerical Simulation Study

Guided wave propagation in the pipe was simulated using COMSOL Multiphysics to analyse the response of the flexural mode to liquid level. A three-dimensional pipe model was established in a cylindrical coordinate system (r, θ, z) with its origin at the center of the cross-section, as shown in Fig. 2, where the r–θ plane coincides with the cross-section and the z-axis is along the axial direction. The model had an inner radius r_i, an outer radius r_o, and an axial length of 198 mm. The material was Zr705 zirconium alloy; see Table 1 for properties and dimensions. To excite the antisymmetric flexural mode, an out-of-plane radial point load was applied on the outer surface at a distance of 36 mm from one end of the pipe. Considering the multimodal nature within the target frequency range, a Hanning windowed 5-cycle sinusoidal signal centered at 100 kHz was used to excite the F(1,1) mode, in order to suppress multimodal and dispersive effects. Monitoring nodes were placed along the same generatrix on the right side of the excitation point, with the first node located 10 mm from the excitation point. A total of 121 surface monitoring nodes were uniformly distributed at a spacing of 0.5 mm to capture the spatiotemporal out-of-plane displacement wavefield. All nodes shared the same circumferential angle as the excitation point to eliminate the influence of helical guided waves [8]. Explicit dynamic analysis was adopted for numerical solution. At the center frequency of 100 kHz, the spatial element size was set to $\Delta x = 1$ mm, corresponding to at least eight elements per wavelength, and the time step was $\Delta t = 0.5$ μs, satisfying the stability condition $\Delta t < 0.8\Delta x/c_{max}$ [9,10]. The total simulation time was 400 μs, covering the entire process of excitation, propagation and monitoring.

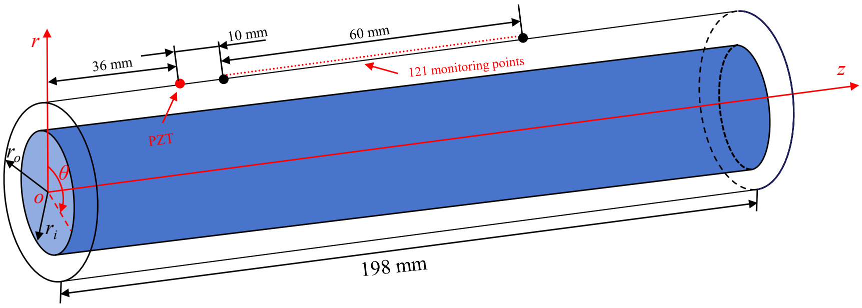

Figure 2 Three-dimensional finite element simulation model of zirconium alloy Zr705 pipeline.

The propagation characteristics of guided waves in empty and water-filled pipes were determined through analysis of the simulation data. Fig. 3(a) and (b) present the frequency–wavenumber spectra obtained via two-dimensional Fourier transform of the simulation results corresponding to the empty and water-filled states, respectively. The results show that the wavenumber of the guided wave in the water-filled pipe is significantly larger than that in the empty pipe. When the frequency–wavenumber spectra are overlaid onto the theoretical dispersion curves of the F(1,1) mode, the regions of energy concentration are found to be in good agreement with the theoretical curves, confirming that the energy propagates predominantly along this single mode. These findings validate the effectiveness of the finite element simulations in exciting the F(1,1) mode, and further demonstrate that this flexural mode can be reliably excited and detected even in liquid-filled pipes.

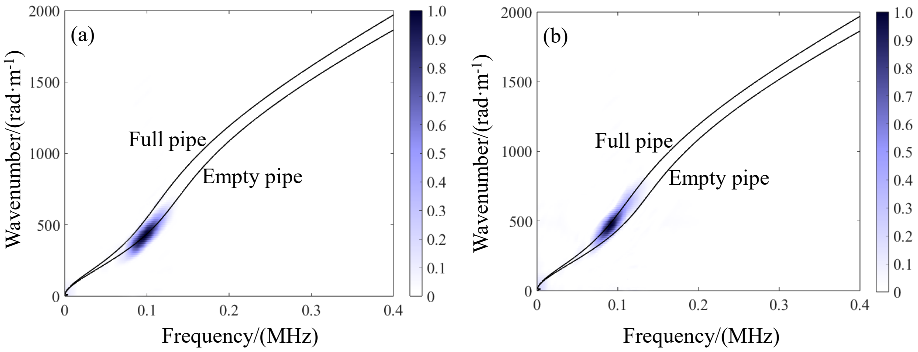

Figure 3 Modal frequency–wavenumber analysis results for the F(1,1) mode in a fluid-filled and empty pipe: (a) simulation results for the empty pipe; (b) simulation results for the fully filled pipe.

3. Pipe Level Measurement

To locate gas–liquid interfaces within pipelines, the influence of liquid loading on guided wave propagation must be elucidated. A point-excitation-based spacing sensing-protocol was designed, and finite element simulations were conducted to systematically analyze guided wave responses under varying water levels; the configuration is illustrated in Fig. 4. The simulations employed point excitation with a 5-cycle Hanning windowed sinusoidal toneburst centered at 100 kHz, with a receiver positioned 100 mm from the excitation source to capture the guided wave response. With the internal water level d_w incrementally varied and the corresponding monitoring signals recorded, the impact of liquid height on propagation behavior was systematically investigated.

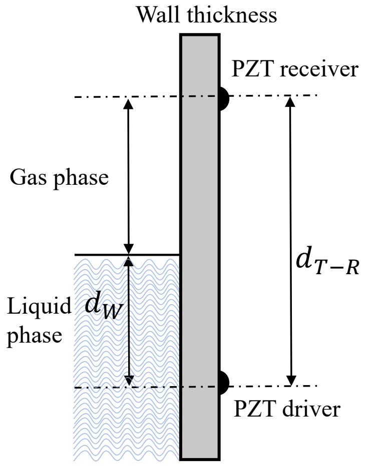

Figure 4 Schematic diagram of signal acquisition device.

According to the distance sensing configuration shown in Fig. 4, the propagation path of the guided wave from the excitation point to the receiving point, d_{T-R}, consists of two segments: the water-submerged segment d_w and the dry segment $d_{T-R} - d_w$. The total travel time t_{T-R} can therefore be expressed as:

$$t_{T-R} = \frac{d_w}{c_{wp}} + \frac{d_{T-R} - d_w}{c_{ep}} \tag{1}$$

Where c_{wp} and c_{ep} denote the group velocities of the F(1,1) flexural mode under water-filled and empty pipe conditions, respectively.

Taking the empty pipe ($d_w = 0$) as a reference, the change in travel time Δt at a given water level d_w relative to the reference state is derived as:

$$\Delta t = d_w \left(\frac{1}{c_{wp}} - \frac{1}{c_{ep}} \right) \tag{2}$$

Equation (2) establishes a quantitative relationship between water-level height and the travel-time shift, providing a theoretical basis for analyzing the changes in guided wave propagation caused by the gas–liquid interface. According to Eq. (2), the travel-time difference Δt is linearly related to the water-level height d_w. To verify this relationship, Fig. 5 presents the guided wave signals obtained from simulations at three water levels ($d_w = 0$, 50 and 90 mm). As the water level increases, the arrival time of the wave packet is progressively delayed and the signal amplitude correspondingly decreases. The travel-time shift Δt at each water level relative to the reference state ($d_w = 0$) was extracted, and the results as function of water level are shown in Fig. 6. The data demonstrate a good linear correlation between the travel-time shift and the water-level height in the simulations, in agreement with the theoretical prediction of Eq. (2). This consistency validates the proposed model and confirms the effectiveness of the flexural mode for quantitative liquid-level detection.

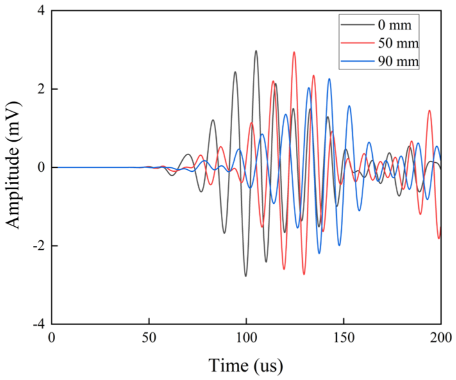

Figure 5 Comparison of simulated results for guided wave responses in liquid-filled piping.

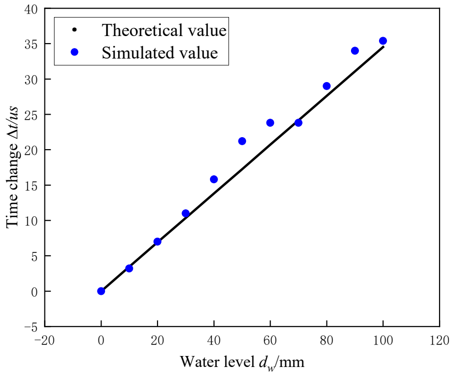

Figure 6 Variation of time difference Δt with measured liquid level d_w.

4. Conclusions

This study addresses the need for liquid-level monitoring in Zr705 zirconium alloy pipes and develops a quantitative detection method based on the F(1,1) flexural-mode ultrasonic guided wave. Dispersion analysis clarifies the difference in dispersive characteristics of this mode between liquid-filled and empty pipe conditions. Combined with finite element simulations using COMSOL Multiphysics and frequency–wavenumber analysis, wavenumber-domain features are extracted, revealing the response of the propagation time delay to the liquid-filled state. Using a pitch-catch configuration, a quantitative mapping model between guided wave characteristic parameters and liquid level height is established. Simulation-based validation demonstrates that the proposed method exhibits good linearity and stability, enabling high-precision inversion of the liquid level. This method is suitable for pipeline condition monitoring in complex industrial environments such as energy and chemical plants.

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