

# Ultrasonic Waveguide for Multiphase Level Monitoring

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## Abstract

In process industries, continuous and accurate level measurement is essential for safe and efficient operation. However, many industrial fluids are inherently heterogeneous, typically forming stratified layers in which solid particles settle at the bottom while lighter components accumulate near the top. Such multiphase conditions complicate reliable level detection, often requiring multiple sensors to quantify the individual layers. This work presents an alternative approach using a single ultrasonic waveguide to detect the overall fill level and liquid layers by exciting multiple acoustic modes. Each mode exhibits a distinct sensitivity to the surrounding medium, enabling the differentiation of layered structures and improving measurement robustness through temperature compensation. Initial investigations in oil–water mixtures show promising agreement between theoretical predictions and experimental results for two of the three targeted wave modes, demonstrating the feasibility of multimodal guided-wave sensing for complex multiphase environments.

## 1 Introduction

Continuous and reliable liquid level measurement is a fundamental requirement in numerous applications of the process industry, including wastewater treatment, chemical processing, and oil–water separation. Conventional measurement principles such as capacitive, hydrostatic, or radar-based sensors typically assume homogeneous fluid properties. As a consequence, their accuracy is significantly reduced or the sensors fail entirely when applied to heterogeneous or stratified media [1]. Numerous studies have demonstrated that industrial fluids frequently exhibit pronounced phase separation, with solid particles settling at the bottom of the container while lighter phases accumulate near the surface. These conditions result in complex multiphase environments that pose substantial challenges for conventional level measurement technologies.

In addition to multiphase effects, practical limitations such as sensitivity to foam formation, mechanical fouling, and limited suitability for aggressive or corrosive media further restrict the applicability of conventional level sensors in industrial environments [1]. As a result, multiple sensors or spatially distributed measurement systems are often required to determine both the global fill level and internal phase boundaries. This increases system complexity, installation effort, and maintenance requirements.

Guided acoustic waves have emerged as a promising approach for structural and process monitoring due to their ability to propagate over long distances and their high sensitivity to changes in the surrounding medium. Previous investigations have shown that different acoustic wave modes, including longitudinal, flexural, and torsional modes, interact in characteristic ways with adjacent fluids and boundary conditions. This behavior enables applications ranging from immersion depth estimation to the detection of material discontinuities and fluid interfaces [2–4]. Most earlier studies focused on metallic waveguides such as aluminum or steel rods, where fill level information was derived from attenuation effects or time of flight

measurements of specific longitudinal modes [2]. However, the susceptibility of metallic materials to corrosion and their comparatively high material costs limit their applicability in chemically aggressive environments.

In this context, polymer-based waveguides, particularly those made of polyethylene, have gained increasing attention due to their chemical resistance, low material cost, and suitability for the excitation of guided acoustic waves [3,4]. Building on these developments, the multimodal excitation of guided waves within a single polymer waveguide offers the potential to extract layer-dependent information without requiring multiple sensor elements.

In particular, previous studies have shown that torsional guided wave modes exhibit only weak sensitivity to external fluid loading while remaining responsive to temperature dependent material property variations, which makes them suitable as reference modes for temperature compensation in multimodal sensing concepts [5].

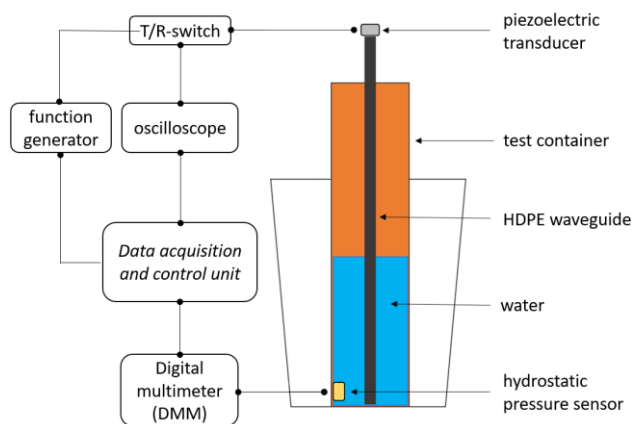
In this work, a polymer based ultrasonic guided wave sensor is investigated that exploits multimodal wave–fluid interactions for robust liquid level measurement in heterogeneous fluids. By selectively exciting acoustic modes with different sensitivities to fluid loading, the proposed approach enables the determination of both the global fill level and internal stratification using a single compact sensing element. Furthermore, the integration of fluid sensitive and fluid insensitive guided wave modes establishes the basis for intrinsic temperature compensation within the same sensor system, reducing the need for additional reference sensors and enabling robust operation in chemically aggressive industrial environments.

## 2 Methods

To investigate the mode specific characteristics with respect to liquid fill level, internal phase boundaries, and temperature dependence, the fill level measurement was validated experimentally and by numerical simulation for longitudinal and flexural guided wave modes. In addition,

the capability of detecting interfacial layer thicknesses was analyzed by means of simulations. This combined experimental and numerical approach allows the individual influence of geometric, material, and environmental parameters to be isolated and systematically evaluated.

In the experimental setup, excitation signals consisting of ten cycle bursts windowed by a Hanning function are generated using a function generator and applied to a piezoelectric transducer mounted at the top end of the waveguide. The excitation frequency is set to 6 kHz, and the same excitation parameters are used consistently in both the experimental measurements and the numerical simulations. The reflected signals of the L(0,1) and F(1,1) guided wave modes are recorded using an oscilloscope for varying liquid fill levels. As a reference measurement for the liquid height, a hydrostatic pressure sensor is integrated at the bottom of the test container and read out by a digital multimeter connected to the data acquisition and control unit (Figure 1).



**Figure 1:** Experimental setup.

The waveguide used in the experiments consists of a high-density polyethylene rod (HDPE) that is vertically immersed in the test container. The choice of a polymer waveguide ensures chemical robustness and enables controlled propagation of multiple guided wave modes. The surrounding medium along the waveguide varies with the liquid fill level, resulting in distinct air coupled and liquid coupled propagation sections.

The selected excitation and evaluation strategy corresponds to a single sensor configuration in which multiple guided wave modes are generated and analyzed using the same waveguide and the same transducer location. This configuration ensures that all observed differences in the measured signals originate from mode specific interactions with the surrounding fluid rather than from spatially separated sensor elements.

The numerical investigations were carried out using a self-developed simulation framework for guided acoustic waves, which has been validated and successfully applied in previous studies [6]. The simulation tool enables the modeling of wave propagation, dispersion effects, and reflections and was adapted to the geometry and boundary conditions considered in this work.

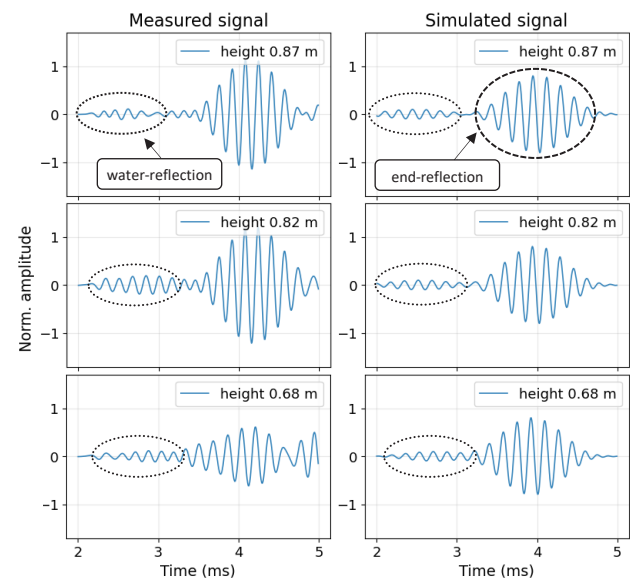
The excitation was applied to a high density polyethylene waveguide with a total length of 1.93 m and a diameter of 40 mm. The waveguide was partially immersed in water at varying fill levels in order to account for relevant fluid structure interactions along the propagation path. The geometry of the waveguide is based on commercially available dimensions and was adopted from previous investigations [1]. The material parameters of the HDPE waveguide were initially taken from manufacturer data sheets. The effective elastic modulus used in the model was experimentally determined [7].

In addition, dispersion curves for the L(0,1) and F(1,1) modes were calculated with the software Disperse for vacuum loaded, water loaded, and oil loaded boundary conditions. This approach allows the influence of external fluid loading on the propagation characteristics of each guided wave mode to be quantified and provides the basis for the mode specific interpretation of experimental time of flight and attenuation effects.

## 3 Results and Discussion

### 3.1 Evaluation of liquid fill level

The comparison between numerical simulations and experimental measurements demonstrates that the theoretically predicted wave propagation behavior of the L(0,1) and F(1,1) guided wave modes shows very good agreement with the measured signals over the investigated range of liquid fill levels. The comparison of experiment and simulation is exemplarily shown for the L(0,1) mode in Figure 2.



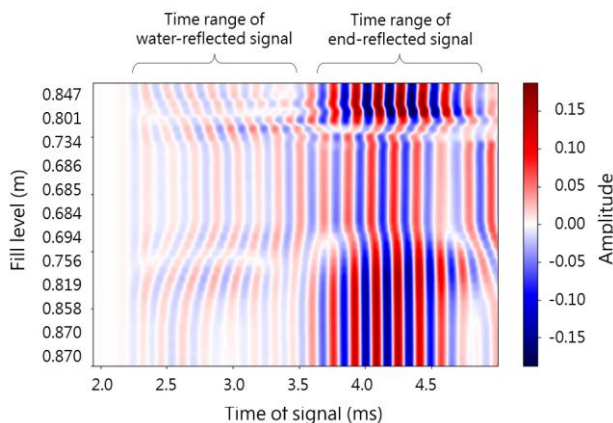
**Figure 2:** Measured (left) and simulated (right) L(0,1) guided wave signals for varying liquid fill levels.

Both the experimental and simulated signals exhibit a consistent shift in the arrival time of the guided wave groups with varying fill level. In addition to the L(0,1) mode, the F(1,1) mode also shows predictable changes in propagation time, confirming its suitability for the detection of the global liquid fill level. In accordance with previous studies,

the F(1,1) mode exhibits a slightly increased sensitivity to the presence of internal phase boundaries compared to the L(0,1) mode, which makes it particularly attractive for the investigation of stratified fluids [5]. Nevertheless, the evaluation of the L(0,1) mode also shows a robust response to fill level variations. The consistent behavior of both modes enables their use as mutual validation for the determination of the overall liquid height.

The very good agreement between numerical predictions and experimental results for both guided wave modes confirms the validity of the simulation approach. This validated simulation framework is therefore used in the following to investigate mode specific effects in more complex multiphase environments, particularly with respect to the identification of internal phase boundaries.

The signal evaluation is performed using classical zero crossing tracking. In this approach, both the time of flight of the water reflected signal and that of the end reflected signal are considered (Figure 3).

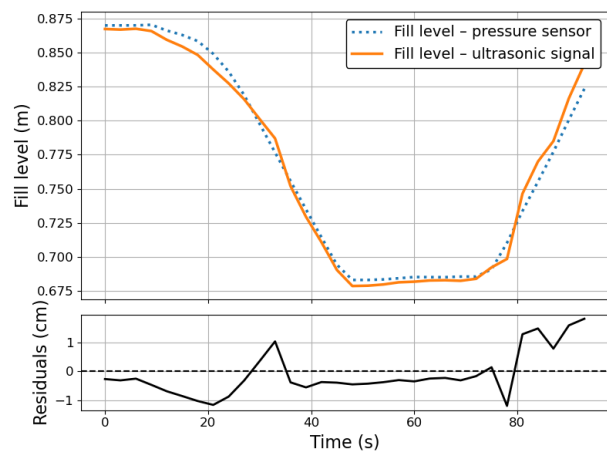


**Figure 3:** Time domain heatmap of measured guided wave signals showing the time ranges of the water reflection and the end reflection for varying liquid fill levels.

Both the water reflected signal and the end reflected signal exhibit systematic temporal shifts as a function of the liquid fill level. When the fill level decreases from 0.87 m to 0.68 m, the water reflected signal shows a delay of up to 0.25 ms. Since this reflection propagates only along the air coupled section of the waveguide, the phase velocity remains constant and the observed time shift results solely from the increased propagation distance in air.

In contrast, the end reflected signal exhibits a smaller shift of approximately 0.04 ms towards earlier arrival times. Although the total propagation distance remains constant, the relative lengths of the air coupled and water coupled sections vary with fill level, leading to a change in the effective average propagation velocity and thus to a fill level dependent arrival time.

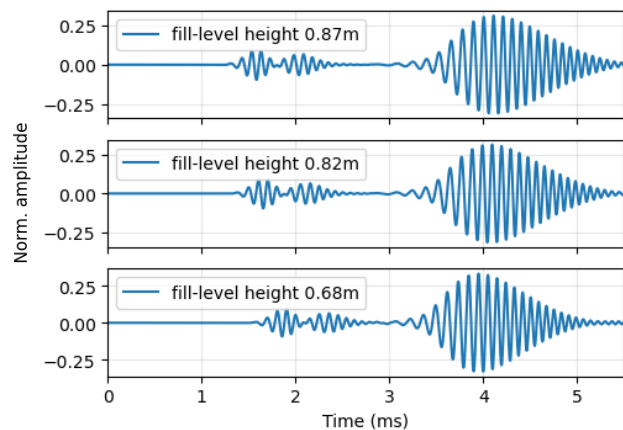
By jointly evaluating both reflections while accounting for the medium dependent propagation velocities, the liquid fill level can be determined relative to the hydrostatic pressure reference. The resulting deviation from the reference measurement remains below 2.0 cm (Figure 4).



**Figure 4:** Comparison of water fill level determined from guided wave measurements and a hydrostatic pressure sensor, including the corresponding residuals.

### 3.2 Evaluation of internal phase boundaries

Building on the validated fill level evaluation, the capability of guided acoustic waves to resolve internal phase boundaries within stratified liquids is investigated in the following. In contrast to homogeneous fluid loading, layered fluid systems introduce additional acoustic impedance contrasts along the waveguide, which result in multiple distinct reflections in the guided wave signal. The simulations contain different time domain signals for an oil-water layered system at different liquid fill levels, corresponding to the conditions investigated in chapter 3.1 (Figure 5).

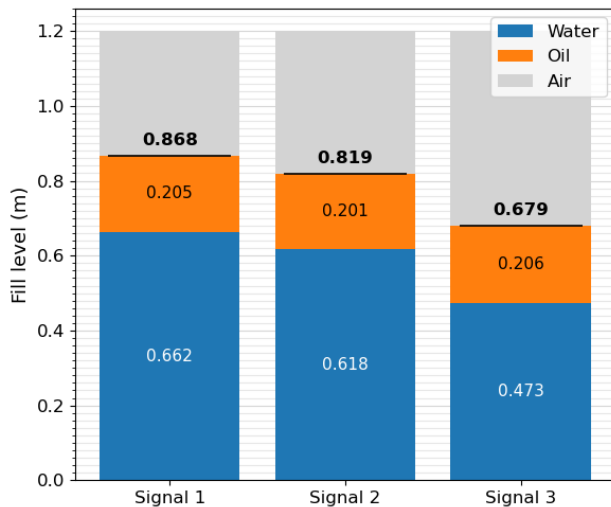


**Figure 5:** Simulated guided wave signals for an oil-water layered system at different total fill levels and an oil-layer thickness of 0.2 m.

In addition to the reflection from the upper oil surface, which corresponds to the global liquid fill level, a second reflection is observed that originates from the interface between the oil and water layers. The temporal separation between these two reflections is governed by the thickness of the oil layer and the effective propagation velocity of the guided wave within the oil loaded section of the waveguide. The final reflection corresponds to the end reflection after propagation along the complete waveguide length. By evaluating the time of flight difference between the reflection from the oil surface and the reflection from the oil-water interface, the thickness of the internal oil layer can

be determined independently of the total fill level. In the present simulations, the oil layer thickness was defined as 0.2 m and serves as a reference value for assessing the accuracy of the proposed evaluation approach.

The resulting decomposition of the total liquid fill level into water, oil, and air contributions is shown in Figure 6.



**Figure 6:** Determined liquid fill level and internal oil-layer thickness.

The oil layer thicknesses reconstructed from the guided wave signals show good agreement with the predefined simulation values for all investigated fill levels. At the same time, the water layer height adapts consistently with the variation of the overall fill level, confirming the internal consistency of the evaluation method.

In contrast to approaches based solely on attenuation or amplitude variations, the presented method relies on geometrically interpretable propagation times. As a result, the evaluation is inherently robust against moderate changes in excitation amplitude and damping behavior. This characteristic makes the approach particularly suitable for applications involving heterogeneous or multiphase fluids, where conventional level measurement techniques often fail to resolve internal interfaces reliably.

## 4 Conclusion

In this work, a polymer based ultrasonic guided wave sensor concept for liquid level monitoring in heterogeneous and stratified fluids was investigated. The presented results demonstrate that longitudinal and flexural guided wave modes provide reliable and consistent information on the global liquid fill level, while numerical simulations and experimental measurements show very good agreement, confirming the validity of the employed modeling approach. By evaluating multiple reflections in the time domain, both the total liquid height and the thickness of internal layers can be reconstructed in a geometrically interpretable manner, resulting in a measurement approach that is inherently robust against amplitude variations and damping effects.

In contrast to conventional metallic waveguide sensors, the use of a high density polyethylene waveguide provides high chemical resistance and enables reliable operation in chemically aggressive media while maintaining a

mechanically simple and cost efficient sensor design. The presented single sensor configuration further reduces system complexity compared to multi sensor measurement solutions, since fill level and stratification information can be obtained using the same compact sensing element.

Future work will focus on the experimental excitation and evaluation of the torsion mode for quantitative temperature compensation and on the validation of a multimodal sensor concept.

## 5 Literatur

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