DOI 10.5162/Ultrasonic2025/A12-b4

Development of a continuous ultrasonic sensor for monitoring the fill level of existing separating layers

Miriam Piechaczek[1], *Alexander Backer*[1], *Tobias Roß*[1], *Sabrina Tietze*[1], *and Klaus Stefan Drese*[1]
[1]*Institute of Sensor and Actuator Technology, Coburg University of Applied Sciences and Arts, Coburg, Germany*
Miriam.Piechaczek@hs-coburg.de

Abstract: A sensor based on guided acoustic waves (GAW) to enable simultaneous detection of fill levels and phase boundaries in heterogeneous media is presented. By exciting longitudinal, flexural, and torsional modes in a polymer based cylindrical waveguide, level measurement, interface detection, and temperature compensation are achieved within a single system. The integration of multiple modes into one sensor reduces system complexity and cost while offering robust performance for industrial applications.

Keywords: Guided Acoustic Waves (GAW), multimodal waveguide, level measurement, multiphase media

Introduction

Level detection in liquid-filled containers is crucial for various industrial applications, such as wastewater treatment, chemical processing, and oil–water separation. Accurate and continuous monitoring of fluid conditions is essential to ensure process safety, operational efficiency, and environmental compliance. However, current sensor technologies suffer from several practical limitations, including sensitivity to foam or sediments, reduced accuracy in multiphase or inhomogeneous media, and incompatibility with aggressive or corrosive fluids [1]. Additionally, most conventional systems are unable to detect internal phase boundaries or sediment layers, particularly under conditions of mechanical fouling or chemical exposure.

Hence, the objective of this study is to present the use of guided acoustic waves (GAW) in polymer waveguides for the reliable detection of fill levels, phase boundaries, and bottom sediments in such challenging environments. Numerical simulations were conducted to explore the mode-specific sensitivities of a multimodal waveguide made from high-density polyethylene (HD-PE). The findings form the foundation for a novel sensor concept that enables not only level measurement, but also temperature compensation and identification of multiphase interfaces through multimode excitation. This approach offers a compact, chemically robust, and cost-effective solution for advanced industrial sensing applications.

Guided acoustic waves offer a promising alternative. Previous studies have shown that acoustic modes propagating in solid rods, particularly longitudinal (L) and flexural (F) modes, are suitable for level measurement. Metallic waveguides made of aluminum or steel have already been used to determine immersion depth through attenuation effects (L(0,2)) or time-of-flight measurements (L(0,1)) [2]. However, metals are costly and prone to corrosion, which limits their use in aggressive environments. Although corrosion-resistant alloys are available, they are often prohibitively expensive. As a result, polyethylene and other polymers are considered attractive alternatives due to their chemical resistance and low cost, and their suitability for acoustic wave excitation is widely discussed in the literature [3] [4]. Despite these advantages, polymers pose specific challenges, particularly modal dispersion and signal attenuation, which complicate the interpretation of acoustic signals [5] [6]. Building on recent developments in waveguide-based sensing technologies [1], this work proposes a multimodal excitation strategy to leverage the distinct physical characteristics of L-, F-, and T-modes. To investigate these properties, finite element simulations were conducted to model wave propagation in a polyethylene rod submerged in water. The simulations aim to evaluate the sensitivity of longitudinal, flexural, and torsional modes to changes in fluid fill level, internal phase boundaries, and temperature. Particular attention is given to the interaction between the waveguide surface and the surrounding medium, as this is expected to affect the modal behavior. The numerical investigation of the different mode sensitivities thus provides a solid foundation for a multimodal sensor concept and practical sensor design.

Materials and Methods

To assess the mode-specific sensitivity of guided acoustic waves in polymer-based waveguides, three-

DOI 10.5162/Ultrasonic2025/A12-b4

dimensional finite element simulations were conducted using COMSOL Multiphysics version 6.1 [7]. To simulate acoustic wave propagation within the HD-PE waveguide, a five-cycle sine burst modulated by a Hanning window at a center frequency of 6 kHz was applied. The generated acoustic wave propagates through the waveguide, reflectes at the opposite end, and returns to the transducer point by which a signal evaluation can be done. The simulation model consists of a cylindrical waveguide (length: $2\,\mathrm{m}$, diameter: $40\,\mathrm{mm}$) that is fully immersed in water to realistically model fluid-structure interactions. The objective of the simulations was to quantify reflection, attenuation, and propagation time variations of individual modes under varying fill levels and temperatures.

The geometry of the rod is based on commercially available dimensions and was adopted from prior investigations [1]. The material properties of high-density polyethylene (HD-PE) at room temperature are summarized in Table 1:

Tab. 1: Material properties of HD-PE at room temperature (20°C).

Parameter	Symbol	Value
Young's modulus	E	$2.2 \times 10^9\,\mathrm{Pa}$
Density	ρ	$960\,\mathrm{kg/m^3}$
Poisson's ratio	ν	0.38

To account for temperature-dependent effects, the Young's modulus was implemented as a function of temperature. The function is based on the COMSOL Multiphysics material database for HD-PE and was normalized to the reference values above [7]. The applied polynomial approximation leading to a Youngs Modulus in GPa and using temperatures provided in K is given by:

$$E(T) = 5{,}770 \times 10^{10} - 4{,}029 \times 10^{8} \cdot T + 9{,}505 \times 10^{5} \cdot T^{2} - 7{,}573 \times 10^{2} \cdot T^{3} \quad (1)$$

Temperature-dependent fluid properties of water were also taken into account using the COMSOL material database.

To analyze the sensitivity of the modes with respect to the fill level, a parameter sweep was performed for the heights $0\,\mathrm{m}$, $0.5\,\mathrm{m}$, $1\,\mathrm{m}$, $1.5\,\mathrm{m}$, and $2\,\mathrm{m}$. An excitation was introduced using a surface source applied to the top face of the rod, and the response signal was measured at a fixed point along the rod's circumference on the same surface.

Additionally, to assess the propagation behavior, dispersion diagrams were generated for the L(0,1), F(1,1), and T(0,1) for a high-density polyethylene (HD-PE) waveguide under two environmental conditions: vacuum and water immersion.

Results and Discussion

The results of the dispersion calculations indicate that both the longitudinal and flexural modes exhibit sensitivity to the surrounding medium (Fig. 1).

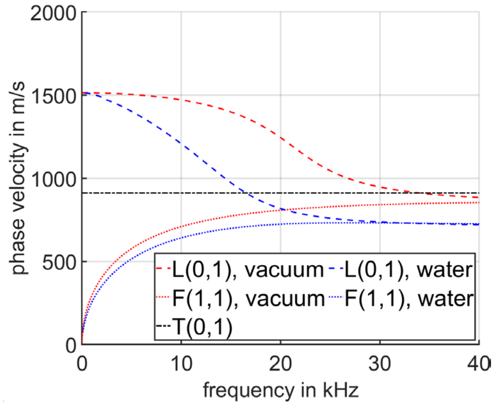

Fig. 1: Dispersion curves for the L(0,1), F(1,1), and T(0,1) modes in vacuum and water.

Specifically, their phase velocities are significantly higher in vacuum (red lines) than in water (blue lines), suggesting a strong interaction with the external fluid. This observation implies that these two modes are well-suited for detecting variations in fluid contact along the waveguide, such as changes in fill level. In contrast, the torsional mode T(0,1) (black line) shows no appreciable difference in phase velocity between vacuum and water, nor across the frequency range considered, as can be seen in Fig. 2.

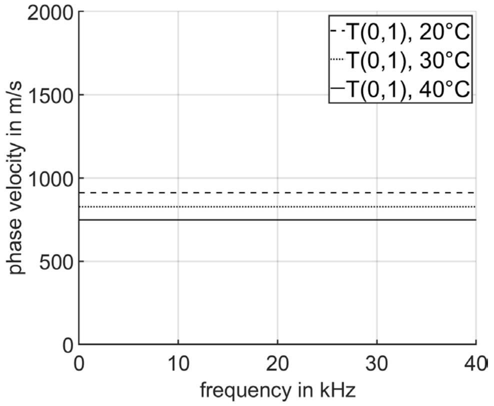

Fig. 2: Dispersion behavior of the T(0,1) mode at different temperatures.

Its velocity profile remains constant and unaffected by the external medium. This non-reactive behavior indicates that the T-mode is insensitive to immersion

DOI 10.5162/Ultrasonic2025/A12-b4

depth or fluid properties and may therefore serve as a stable reference in multimodal sensing configurations due to its remaining sensitivity to temperature variations.

To evaluate the influence of both the surrounding medium and temperature, further dispersion curves were generated for the L(0,1) and F(1,1) modes at 20 °C, 30 °C, and 40 °C, each in vacuum and in water. The results show a clear reduction in phase velocity not only when transitioning from vacuum to water, but also with increasing temperature for the longitudinal and flexural modes. Specifically, the F(1,1) mode exhibits a reduction of approximately 75 m/s in phase velocity for a temperature increase of 20 °C, both in vacuum and in water, at an excitation frequency of 6 kHz (Fig. 3).

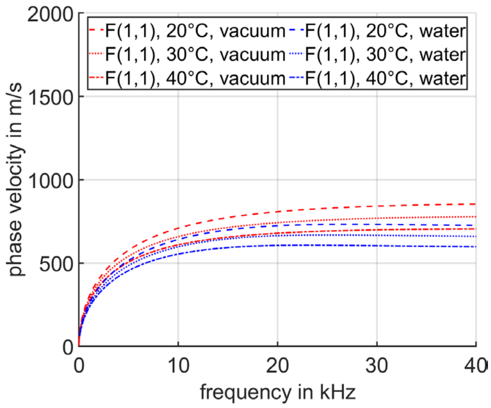

Fig. 3: Dispersion behavior of the F(1,1) mode at different temperatures and medium conditions.

In comparison, the L(0,1) mode shows a stronger reduction of about 280 m/s in vacuum and 250 m/s in water over the same temperature range at 6 kHz. (Fig. 4)

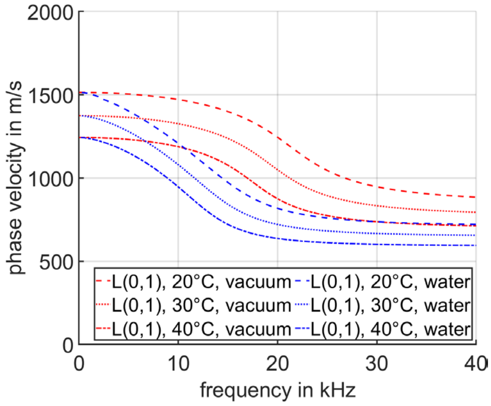

Fig. 4: Dispersion behavior of the L(0,1) mode at different temperatures and medium conditions.

This dual sensitivity toward both medium and temperature indicates that changes in environmental conditions affect wave propagation significantly. Consequently, accurate fill level determination using these modes requires temperature compensation to avoid erroneous interpretations.

To further verify the mode sensitivities, time-domain signal analyses were conducted. The torsional mode was first examined under vacuum conditions at various temperatures (Fig. 5).

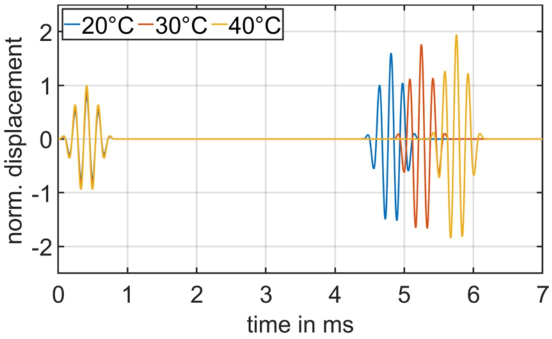

Fig. 5: Time signals of the torsional mode at 20°C, 30°C and 40°C in vacuum.

While the initial excitation pulses (left) overlap perfectly across all three temperatures (20°C, 30°C, and 40°C), the respective and reflected end signals (right) show a clear temporal shift. Specifically, the arrival time increases with temperature: the signal at 20°C arrives earliest, followed by 30°C and 40°C. This confirms the temperature-dependent propagation velocity of the T(0,1) mode, as proven by the examination of the dispersion (Fig. 2).

For the final analysis, time-domain signal evaluations of the three wave modes were performed at room temperature with varying fluid levels of the surrounding water(Fig. 6).

For the longitudinal (L) and flexural (F) modes, intermediate signal reflections were observed between the initial excitation (left) and the final reflection (right), after the wave had traversed the entire length of the waveguide. These intermediate reflections are attributed to interactions with the fluid medium, where higher filling levels lead to earlier reflection events corresponding to the fluid's upper boundary. In comparison, the flexural mode exhibits higher reflection amplitudes than the longitudinal mode, suggesting a potentially greater suitability for detecting fill level variations or identifying phase boundaries in stratified media. Specifically, the longitudinal mode returns approximately 4% of the excitation amplitude as a reflection signal, whereas the flexural mode reflects about 14%, further highlighting its stronger sensitivity to fluid interaction.

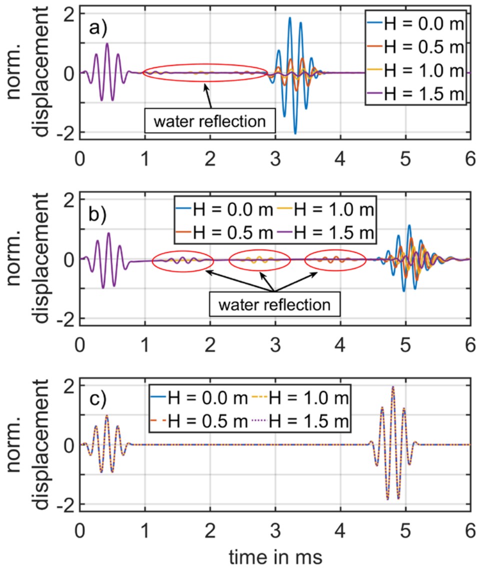

Fig. 6: Signal analysis for a) longitudinal mode b) flexural mode and c) torsional mode at different fluid levels (T=20°).

The varying arrival times of the end reflections are explained by the different group velocities of the wave modes, with the longitudinal mode (L) propagating fastest, followed by the torsional and flexural modes. The larger amplitude of the reflected end signals compared to the initial excitation signal can be attributed to constructive interference occurring at the rod termination during wave reflection.

Conclusion and Outlook

This study presents a numerical investigation of guided acoustic wave propagation in a polymer-based waveguide for simultaneous sensing of fill level, temperature, and phase boundaries. By selectively exciting and analyzing longitudinal, flexural, and torsional wave modes in a high-density polyethylene rod, distinct sensitivities toward environmental conditions were identified.
The results demonstrate that:

- The torsional mode T(0,1) is unaffected by contact with water and exhibits only temperature-dependent propagation characteristics, making it a reliable basis for temperature compensation.
- The longitudinal mode L(0,1) responds to both fill level and temperature changes, with measurable reflections at fluid interfaces, suitable for coarse interface detection.
- The flexural mode F(1,1) shows the highest sensitivity to fill level and phase boundaries, with strong signal modulation depending on immersion depth and surrounding medium.

These findings highlight the potential of a multimodal sensing strategy using guided acoustic waves in low-cost, chemically robust polymer materials. The integration of multiple wave modes within a single sensing element enables a compact and versatile sensor design capable of compensating for environmental cross-sensitivities. In the next steps, experiments will validate the theoretical findings. This includes the experimental characterization of mode behavior under varying fluid conditions and comparison of measured data with simulation results.

Acknowledgement

This research was funded by the German Federal Ministry of Research, Technology and Space (BMFTR) for the project KonUsT under grant number 02P24K111.

References

[1] K. Lutter, A. Backer, and K. S. Drese. "Guided Acoustic Waves in Polymer Rods with Varying Immersion Depth in Liquid". In: *Sensors* 23 (2023), p. 9892. DOI: 10.3390/s23249892.

[2] N. Subhash and B. Krishnan. "Fluid level sensing using ultrasonic waveguides". In: *Insight* 56 (2014), pp. 607–612. DOI: 10.1784/insi.2014.56.11.607.

[3] J. Shah, S. El-Hawwat, and H. Wang. "Guided Wave Ultrasonic Testing for Crack Detection in Polyethylene Pipes: Laboratory Experiments and Numerical Modeling". In: *Sensors* 23 (2023), p. 5131. DOI: 10.3390/s23115131.

[4] J. S. Egerton et al. "Ultrasonic attenuation and phase velocity of high-density polyethylene pipe material". In: *The Journal of the Acoustical Society of America* 141 (2017), pp. 1535–1545. DOI: 10.1121/1.4976689.

[5] H. Kwun, K. A. Bartels, and C. Dynes. "Dispersion of longitudinal waves propagating in liquid-filled cylindrical shells". In: *The Journal of the Acoustical Society of America* 105.5 (1999), pp. 2601–2611. DOI: 10.1121/1.426876.

[6] P. D. Wilcox. "A rapid signal processing technique to remove the effect of dispersion from guided wave signals". In: *IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control* 50.4 (2003), pp. 419–427. DOI: 10.1109/tuffc.2003.1197965.

[7] COMSOL Inc. *COMSOL Multiphysics: Simulate Real-World Designs, Devices, and Processes with Multiphysics Software*. https://www.comsol.com. Accessed: 2025-07-11. 2025.