DOI 10.5162/EUROSENSORS2025/TP48

Novel Acoustic Method for Detecting Fluid Phase Boundaries

Marcel Kamrad [1], Jens Rautenberg [2], Leonhard Reindl [1], Katrin Schmitt [1] and Jürgen Wöllenstein [1]

[1] University of Freiburg, Department of Microsystems Engineering - IMTEK, Georges-Köhler-Allee 102, 79110 Freiburg Germany
[2] Endress+Hauser Flow Deutschland GmbH, Rosenauer Str. 27, 96450 Coburg, Germany

marcel.kamrad@imtek.uni-freiburg.de

Summary: This work presents a novel, non-invasive sensing approach based on leaky lamb wave for detecting phase boundaries between immiscible fluids. The development of this approach is ongoing and utilizes the sensitivity of quasi-guided waves to fluid-specific properties such as density and speed of sound. Variations in these properties influence wave attenuation and time-of-flight characteristics. By analyzing these characteristics, the system enables precise and contactless localization of fluid interfaces.

Keywords: Phase Boundary Detection, Leaky Lamb Waves, Acoustic Sensing, Fluid Density, Speed of Sound, Non-Invasive Measurement

Introduction

Accurate detection of phase boundaries between immiscible fluids with differing physical properties - such as density and speed of sound - is crucial across a broad spectrum of industrial processes. These include chemical and petrochemical production, phase separation systems, and the monitoring of liquid-liquid or liquid-gas interfaces within storage tanks and process vessels [1]. Conventional sensing methods, such as invasive probes, optical sensors, and radiation-based systems, often suffer from significant limitations. These include fouling, mechanical wear, complex safety requirements, and sensitivity to contamination. Such constraints can compromise long-term reliability and operational efficiency [2]. To overcome these limitations, we propose a novel, non-invasive sensing method based on the excitation and analysis of quasi-guided surface acoustic waves. This technique enables precise and contactless detection of fluid interfaces through the walls of containers (e.g., pipes or tanks), without direct exposure to the process media.

Sensor Concept and Operating Principle

The proposed sensing concept utilizes leaky Lamb waves that are excited in the walls of fluid-containing structures, such as tanks or pipes, as illustrated in Fig. 1. These quasi-guided waves propagate along the solid boundary, while part of their energy leaks into the adjacent fluid at a defined angle - known as the coincidence angle - which depends on the phase velocity of the Lamb waves and the speed of sound of the fluid. The radiated acoustic energy travels across the fluid, interacts with the opposite wall of the tank, and re-couples into the structure where it again leaks into the fluid, forming distinct propagation paths (e.g., direct path, I-path, V-path) [3]. These wave groups are received by dedicated transducers, and variations in signal characteristics are analyzed to infer the position of the fluid interface.

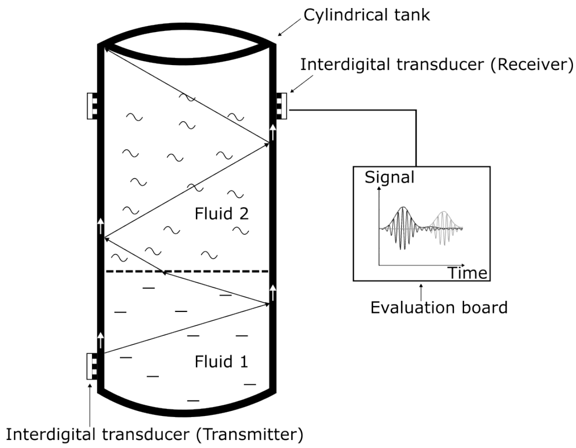

Fig. 1: Sensor concept and operating principle.

The detection mechanism is sensitive to the acoustic properties of the fluids, as described for a homogeneous fluid system in [4]. Variations in density and sound velocity affect both the coincidence angle and wave attenuation. At the interface between two immiscible fluids, partial reflection, transmission, and refraction occur, governed by Snell's Law. These interactions are characterized by acoustic impedance mismatches and also result in measurable changes in amplitude and propagation time.

DOI 10.5162/EUROSENSORS2025/TP48

Results

The characteristics of wave propagation under fluid loading were characterized by solving the dispersion relations of Lamb waves, incorporating the complex wavenumber to account for attenuation effects [4]. The analysis focused on the fundamental symmetric and antisymmetric modes in a stainless steel plate (material properties: $c_p = 5750\,\mathrm{m/s}$, $c_s = 3150\,\mathrm{m/s}$, $\rho = 7950\,\mathrm{kg/m^3}$) loaded on one side with two representative process fluids: water ($\rho = 1000\,\mathrm{kg/m^3}$, $c = 1500\,\mathrm{m/s}$) and oil ($\rho = 800\,\mathrm{kg/m^3}$, $c = 1250\,\mathrm{m/s}$). The resulting coincidence angles and attenuation coefficients for both fluid cases are depicted in Fig. 2.

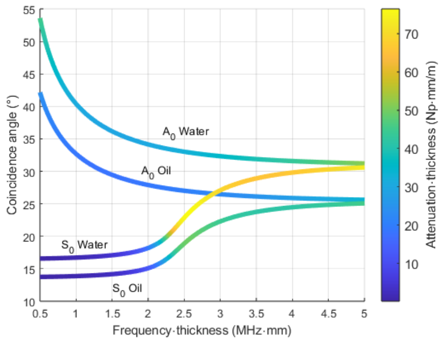

Fig. 2: Coincidence angle and attenuation for a one-sided fluid-loaded stainless steel plate with fundamental Lamb-wave modes.

A two-dimensional model was implemented, consisting of two parallel plates separated by a distance of $h = 2\,\mathrm{cm}$, with a transmitter–receiver distance of $D = 7\,\mathrm{cm}$. The fundamental antisymmetric A_0 mode was excited at a frequency–thickness product of $1\,\mathrm{MHz \cdot mm}$. The propagation time of I-path signal was evaluated for various fluid configurations and different positions of the phase boundary, as shown in Fig. 3. The corresponding relative signal amplitudes for both the direct path (on the transmitting plate) and the I-path (on the receiving plate) are presented in Fig. 4 for water and oil. An exponential decay of the direct path amplitude is observed, which results from the continuous leakage of energy into the adjacent fluid medium. Simultaneously, the amplitude of the signal on the receiving plate increases due to energy radiation from the transmitting plate and subsequently undergoes exponential attenuation along the I-path.

Conclusion and Outlook

We have introduced a non-invasive sensing technique based on the excitation of leaky Lamb waves for detecting phase boundaries between immiscible fluids. The presented sensitivity study promises accurate interface localization without direct fluid contact, offering substantial advantages over conventional methods.

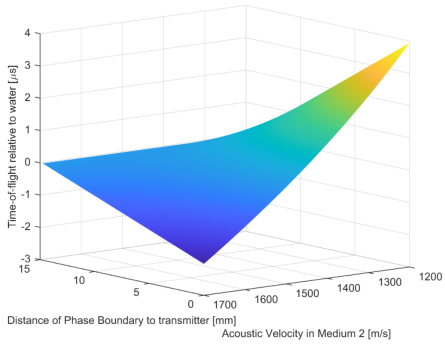

Fig. 3: Time-of-flight for the I-Path relative to water for different acoustic velocities for the second fluid and different phase boundary positions.

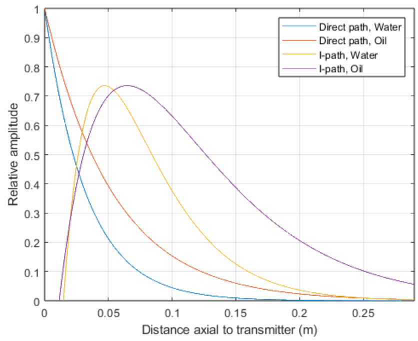

Fig. 4: Relative amplitudes for direct path and I-path for water and oil.

Future work will focus on improving system accuracy. In particular, the influence of temperature on the signal will be examined. Finally, extensive comparisons between simulations and experimental data will be conducted to validate the proposed sensing concept.

References

[1] G. Lu, et al., A new-type sensor for monitoring oil-water interface level and oil level, *2009 9th International Conference on Electronic Measurement & Instruments*, Beijing, China, 2009, pp. 2-981–2-983; doi: 10.1109/ICEMI.2009.5274393

[2] S. Hassani, U. Dackermann, A Systematic Review of Advanced Sensor Technologies for Non-Destructive Testing and Structural Health Monitoring, *Sensors* 23, 2204 (2023); doi: 10.3390/s23042204

[3] G. Lindner, et al., Wave Propagation in an Acoustic Wave Guide Sensor for Liquids Driven by Pulsed Excitation of Surface Acoustic Waves, *IEEE Frequency Control Symposium*, Honolulu, HI, USA, 2008, pp. 39-43, doi: 10.1109/FREQ.2008.4622952

[4] J. Rautenberg, et al., Utilizing Leaky Lamb Waves in an Acoustic Waveguide for the Measurement of Liquid Properties, *Proceedings SENSOR 2013*, 74–79; doi: 10.5162/sensor2013/A3.3