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Optimization of Ultrasound Coupling for Clamp-on Flowmeters Using FEM Tools

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Summary:
Many state-of-the-art flowmeters are based on ultrasonic time-of-flight measurements. To enable an easy, fast and low-cost clamp-on mounting with an appropriate signal level, the materials and geometries must be tailored accordingly. Within this study, various materials for coupling wedges and matching-layers were evaluated with respect to acoustic impedance and transmission performance using the finite element method (FEM). Additionally, the incidence angle between the transducer and the fluid interface was optimized to maximize energy transfer and to minimize reflections. The simulation results were then compared with experimental measurements, showing improved signal quality and consistency across different setups. In future work these highly accurate measurements will be used for an AI-based leakage detection.

Keywords: Ultrasound coupling, FEM Simulation, clamp-on flowmeter, leakage detection, AI algorithm

Introduction

Ultrasonic (US) based flowmeters are state-of-the-art for accurate flow measurements [1]. Due to high impedance differences between solids and liquids, coupling conditions are critical for high-precision flow measurement, especially using clamp-on flowmeters. These systems can be based on externally mounted ultrasonic transducers transmitting acoustic waves through a coupling wedge, a matching-layer and finally the pipe wall into the fluid without direct contact to the fluid. Energy losses occur at interfaces between transducer, wedge, matching-layer, and the target fluid, primarily due to impedance mismatches and suboptimal geometrical alignment.

Within this study, several strategies for optimization of US coupling setups were investigated to overcome these limitations. The optimized setup will be used to develop an AI-based algorithm for leakage detection.

Simulation and Experimental Setup

The ultrasonic wave propagation in the clamp-on flowmeter setup is simulated using a two-dimensional finite element model in COMSOL Multiphysics. The simulation approach is based on a time-explicit transient analysis using the discontinuous Galerkin finite element method (dG-FEM). The elastic wave propagation in solids and acoustic wave propagation in fluids (water in this case) is modelled in a coupled framework. The dG-FEM is chosen due to its robustness and accuracy in handling material interfaces with high impedance contrasts - particularly critical at the solid-fluid boundary - and its suitability for transient high-frequency (MHz) simulations [2]. The 2D mode reduces the model size significantly and lowers calculation time while maintaining sufficient physical accuracy. The calculation time would be prohibitively high for full 3D simulations, especially for transient simulations in the MHz regime.

The geometry consists of two ceramic PZT (lead zirconate titanate) piezoelectric transducers, each of which is attached to a coupling wedge with a matching-layer, mounted on the same side of a water-filled pipe. The transducers, coupling wedges and matching layers are identical in size and are arranged in a mirror-symmetric configuration (see Figure 1).

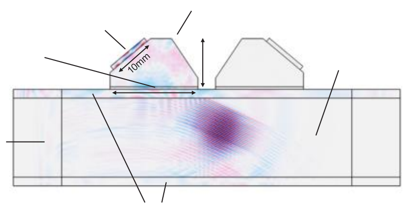


Figure 1: Geometry of the FEM model and a simulated pressure field (30 µs after excitation)

One transducer acts as the transmitter (Tx) and the other as the receiver (Rx). The acoustic waves emitted by the transmitter pass through the wedge and matching-layer into the fluid through the pipe wall. These waves then reflect off the lower wall and return on a mirrored path to be received by the Rx transducer. Additionally, structure-borne sound propagates directly through the pipe wall and reaches the receiving transducer before the fluid-borne reflection arrives. This early-arriving signal is relevant for the interpretation of the received waveform (cf. Figure 2). The coupling wedge with the attached Rx transducer is always placed centrally at the point on the pipe where the impinging sound waves generate the highest acoustic pressure. To prevent reflections from the domain boundaries, absorbing layers were added to both pipe ends of the FEM model. Simulations were carried out on pipes made of steel, copper, and PVC, with outer diameters and wall thicknesses conforming to DIN 15 standards.

Various coupling wedge materials (e.g., PMMA, POM-C, PTFE) and matching-layer materials (e.g., PU-tape, silicone-tape, silicone grease) were tested. Simulations were carried out with various wedge geometries at different angles between the transducer and the pipe wall to determine the optimum angle of incidence at the matching-layer/pipe-wall interface for total internal reflection of longitudinal waves while maximising the coupling of transverse waves. Suppressing unwanted longitudinal modes prevents signal corruption and enhance primary shear wave transmission [3]. A unipolar square-wave burst of 10 pulses with an amplitude of 5 V, a duty cycle of 50 % and a frequency of 2 MHz is used as the excitation signal. For each case, the electrical voltage at the receiving transducer is evaluated to assess the efficiency of the ultrasound coupling.

Results

Figure 2 shows a direct comparison of simulated and measured waveforms. The shapes of the time-domain waveforms and their arrival times match closely, validating the simulation model. However, the simulated amplitudes are around 40 % smaller than the measured values. A possible explanation for this is that the literature values of the material damping ratios used in the simulation differ slightly from the actual damping ratios.

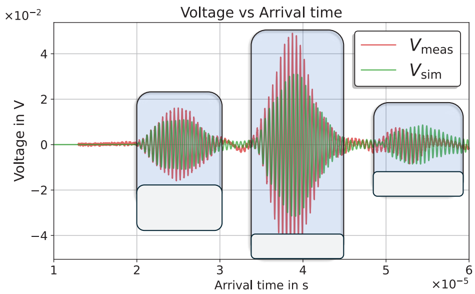
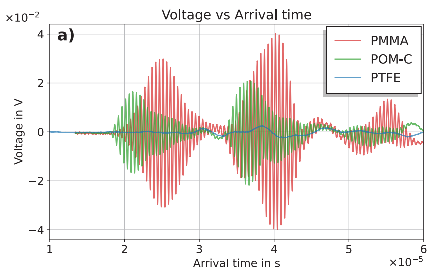


Figure 2: Comparison of simulated and measured time-domain voltage waveforms (DIN 15 steel pipe)

Figure 3 illustrates the experimentally determined waveforms, using different wedge- and matching-layer materials. Among all tested configurations, PMMA as the coupling wedge material combined with a silicone grease matching-layer yielded the highest received signal amplitude and -integrity.



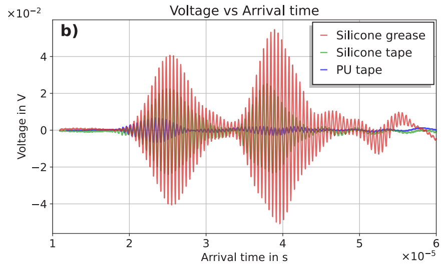


Figure 3: Measured waveforms for different wedge- (a) and matching-layer materials (b) (DIN 15 steel pipe)

Figure 4 presents the simulated waveforms at different incidence angles for a DIN 15 steel pipe. The best sensitivity and waveform integrity for the steel pipe is achieved at a coupling angle of 35°. For copper and PVC pipes of equivalent dimensions, the optimal angle shifts to 40°, where similar improvements in sensitivity and signal coherence are observed. These angles thus represent the optimal configurations for each pipe material and the given geometry.

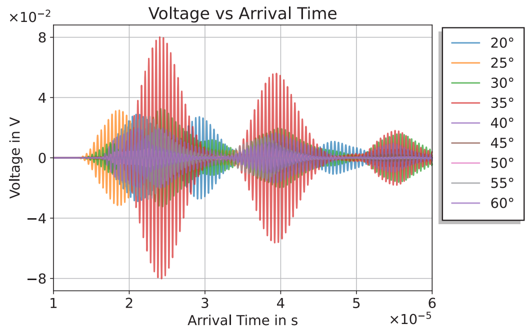


Figure 4: Simulated waveforms for different incidence angles (DIN 15 steel pipe)

Conclusions

This study shows the optimization of ultrasonic transmission of clamp-on transducers into liquid-filled pipe systems. Signal integrity and sensitivity can be significantly improved by optimizing the geometry and material configuration of coupling elements. Finite element simulations and measurements were conducted to evaluate various wedge and matching-layer materials, as well as to determine the optimal incidence angle for efficient energy transfer. The simulated waveforms closely match the experimental data, validating the model approach. The high-quality US measurement enables the application as leakage sensor. In further research an AI based algorithm will be developed to detect leakage in pipe systems.

References

[1] J. Senthil et al., A comprehensive review on accuracy in ultrasonic flow measurement using reconfigurable systems and deep learning approaches, *AIP Advances 10(10):105221 (2020);* doi: 10.1063/5.0022154

[2] J. D. Achenbach, Wave Propagation in Elastic Solids, *North-Holland*, (1973)

[3] W. Hu et al., Mode conversion and critical angle effects in ultrasonic flow sensors, *Proc. of ICISMME 2015 (Atlantis Press)*, pp. 1057–1060 (2015)