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Ultrasonic Flow Measurement Using Guided Acoustic Waves: Application of Cylindrical Modes in Pipe Systems

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Abstract: This paper explores an alternative approach to ultrasonic flow measurement using guided acoustic waves in cylindrical modes. Unlike conventional methods with diagonal sound propagation, the entire pipe including the fluid is excited to vibrate, reducing path-dependent correction factors. A ring-shaped sensor was developed for a DN15 steel pipe. Results show a signal time shift 2.5 times greater than with Lamb wave-based sensors, adjustable over distance. This approach enables precise, non-invasive flow measurement across various pipe diameters.

Keywords: Flow metering, non-invasive flowmeter, ultrasonic flow measurement, guided acoustic waves, cylindrical modes

Introduction

Ultrasonic flow measurement in pipes has been established in industrial environments for many years. It is a precise, cost-effective and, above all, non-invasive method for measuring volume flows. In addition to variants with piston transducers and wedge transducers, in which sound is transmitted diagonally through the fluid once with and once against the direction of flow, guided acoustic waves are also used that couple out into the fluid [1, 2]. An essential common feature of these methods is the measurement along a sound path, which means that there are dependencies on the flow profile and correction factors are therefore required. The angle of the sound path directly influences the measured signal time shift. This means that the sensitivity of the measuring device when using guided waves is media-specific and can hardly be influenced by design. An approach that differs from the diagonal sound paths is the use of guided acoustic waves in the form of cylindrical modes. This involves sound propagation along the pipe, whereby the entire pipe and the fluid are excited to oscillate. Interaction with the entire fluid eliminates the need for path-dependent correction factors. In addition, this results in a much longer effective measurement path compared to diagonal transmission. This is not determined by the flowing medium but by the sensor distance, which also increases the signal time shift to be analysed. Due to the longer effective measuring distance, the cylindrical modes are already used for measuring the smallest flow rates in very thin pipes and cannulas [3]. The possibility of extending the approach to significantly larger pipe diameters has now been tested on a DN15 pipe.

Selection of suitable modes

For most common ultrasonic flow sensors with piston or wedge transducers, the angle of the sensors or wedge used is particularly important. In addition, a frequency suitable for the fluid and the pipe geometry must be selected. With Lamb wave-based flow sensors, on the other hand, the propagation and decoupling behaviour of the different Lamb modes must be taken into account. The selection of a suitable mode and measuring frequency is crucial here. The sensitivity of the sensor to a fluid flow resulting from the choice of operating point and can be determined by the convection coefficient [2]. This is shown for the material and fluid properties specified in Tab. 1 in figure 1.

Tab. 1: Sensor geometries and material parameters at $20\ ^\circ\mathrm{C}$ *[4].*

Tube Geometry		
Inner diameter	b	$15\ \mathrm{mm}$
Wall thickness	d	$1.5\ \mathrm{mm}$
Tube Properties		
Young's modulus	E	$193.8\ \mathrm{GPa}$
Poisso's ratio	ν	0.294
Density	ρ	$7969.0\ \mathrm{kg/m^3}$
Water Properties		
Speed of Sound	c_f	$1481.5\ \mathrm{m/s}$
Density	ρ	$998.2\ \mathrm{kg/m^3}$

A typical operating point of a Lamb wave ultrasonic flow sensor is marked with a red circle in Fig. 1.

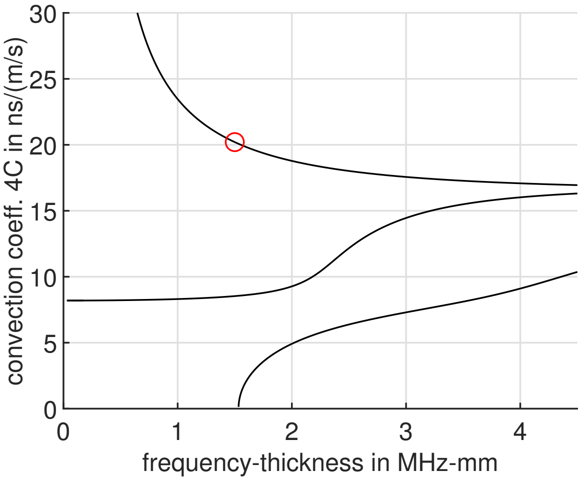

Fig. 1: Convection Coefficient for a Lamb wave based ultrasonic flow meter.

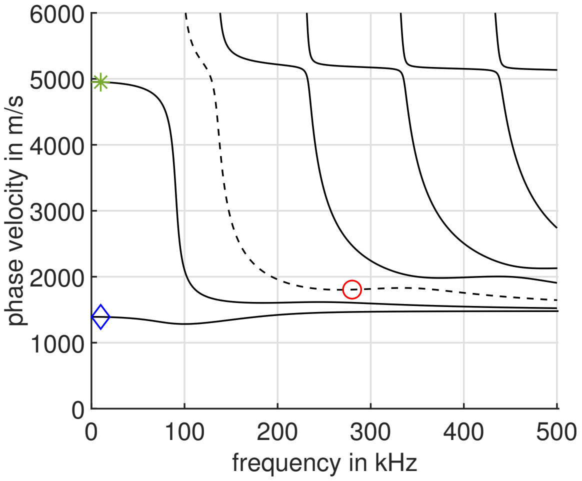

Fig. 2: Phase velocity diagramm of a fluid filled steel pipe. 0^{th} circumferential order.

The example used represents a sensor with water flowing through it, which consists of two $1.5\ \mathrm{mm}$ thick, parallel steel plates, with $15\ \mathrm{mm}$ distance to each other. The mode used here is the $A0$ mode at an excitation frequency of $1\ \mathrm{MHz}$. The convection coefficient is calculated for a V-path configuration. The fluid is therefore sonicated twice in and twice against the flow direction. At a flow velocity of $1\ \mathrm{m/s}$, this results in a transit time difference of approx. $20\ \mathrm{ns}$.

In contrast to Lamb waves on plates, acoustic waves propagate on pipes in the form of cylindrical modes. There are longitudinal, flexural and torsional modes (L-, F-, T-modes). Due to the ring-shaped closed system of a pipe, azimuthal vibrations can also occur. These are numbered with the circumferential order starting at 0. In the case of a pipe filled with liquid, the interaction with the fluid and the sound propagation in the fluid results in additional modes with different vibration modes inside the fluid [5].
With the large number of possible modes, it is now necessary to find a suitable mode for the flow measurement. This paper focuses on the 0^{th} circumferential order. The phase velocity is shown in Fig. 2 and the group velocity of the modes forming in a steel pipe filled with water is shown in Fig. 3. The exact material properties and pipe geometries are listed in Tab. 1.

When selecting a suitable mode and operating frequency, three points are particularly important. The first is the mode purity in the received signal. In addition to a dominant excitation by an optimised sensor geometry, this can be achieved by selecting a suitable operating point in the dispersion diagram of the group velocity and thus the time separation from other modes. Three operating points selected as examples are labelled red, green and blue in Fig. 2. The second point is the excitability and detectability of the mode. This is directly related to the third point, the sensitivity of the mode to a fluid flow. An initial estimate of this can be made using the axial power flow. Like the dispersion diagrams, this was calculated using the DISPERSE software [5]. It shows the spatial distribution of the axial power flow along the pipe across the pipe cross-section. In Fig. 4, this is shown for the positions marked in colour in Fig. 2 resp. Fig. 3.

The green and blue markings and the green and blue lines represent two extreme situations. In the former, the energy of the wave is transported almost exclu-

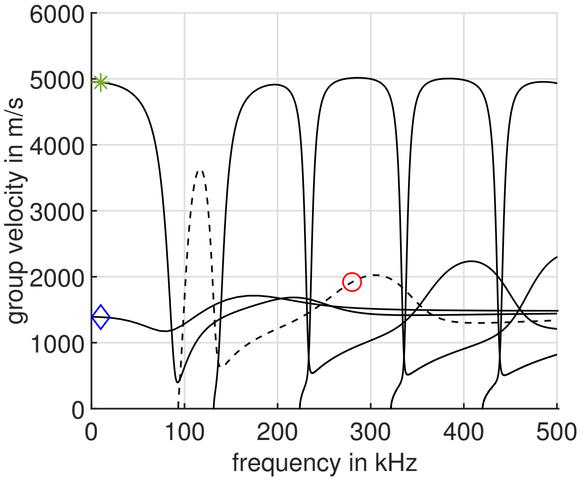

Fig. 3: Group velocity diagramm of a fluid filled steel pipe. 0^{th} circumferential order.

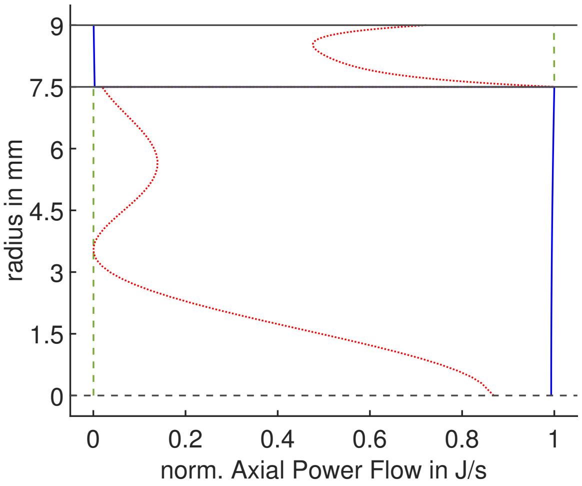

Fig. 4: Axial Power Flow of a fluid filled steel pipe.

sively in the pipe wall. This enables good excitability and detectability of the mode by an ultrasonic sensor attached to the pipe. However, since almost no energy is transported in the fluid, the mode hardly reacts to a fluid flow and is therefore unsuitable for a flow sensor. The blue curve represents the second extreme. Here, almost the entire energy of the mode is transported in the fluid. Although this means excellent sensitivity to fluid flow, it makes the mode extremely difficult to excite and detect. As shown in [3], it is possible to build a flow sensor with this mode, but it requires high signal amplification and at the same time massive attenuation of unwanted modes. The latter is difficult to realise with a DN15 pipe.

The third, red operating point represents a compromise between excitability and detectability as well as sensitivity to a fluid flow. In combination with excitation that is as mode-pure as possible through the sensor geometry and separation from other modes through a suitable group velocity, all conditions for the construction of an ultrasonic flow sensor are thus fulfilled.

Sensor configuration and measurement setup

Since the selected mode is one of the 0^{th} circumferential order, a ring-shaped sensor configuration was used. The sensor shown in Fig. 5 consists of 22 square piezoceramics. The sensors manufactured by PI Ceramic GmbH from PIC255 have an edge length of $2.54\ \mathrm{mm}$ and are equally distributed around the tube. A $100\ \mathrm{\mu m}$ thick indium foil is located between the tube surface and the piezoceramic, which deforms when the piezoceramics are pressed against it by tightly wrapping it with dental floss and enables good sound transmission between the tube and the sensor. Electrical contact was made via the tube and a copper wire wrapped in the dental floss.

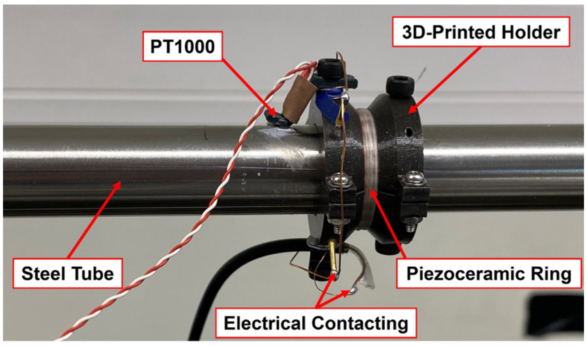

Fig. 5: One side of the ultrasonic flow meter with electrical connections and PT1000 temperature sensor.

Two of these sensors were attached to the $1.6\ \mathrm{m}$ long DN15 pipe at a distance of $200\ \mathrm{mm}$. The pre-flow distance between the first sensor and the nearest pipe coupling was $1\ \mathrm{m}$. The assembled measuring tube was then measured in the water test rig shown in Fig. 6. The flow rate was controlled via the speed control of a centrifugal pump. The Promass Q Coriolis sensor from Endress+Hauser was used as the reference sensor. A Keysight 33500B function generator was used to simultaneously excite the two sensors and a Teledyne LeCroy HDO6054B oscilloscope was used to detect the received signals. Switching between transmitting and receiving was realised by a two-channel multiplexer. A $20\ \mathrm{V_{peak-peak}}$, $280\ \mathrm{kHz}$, 10-fold sine burst with Hanning windowing was used as the transmission signal.

Measurement results and discussion

The two simultaneously recorded received signals were cross-correlated with each other and the time shift was determined. Fig. 7 shows the flow rate determined by the Coriolis sensor and varied via the pump speed on the left y-axis. The corresponding displacement of the ultrasonic signal is plotted on the right y-axis. Before the start and at the end of each measurement, the flow was completely stopped by closing the valves in order to obtain a zero line and thus a reference.

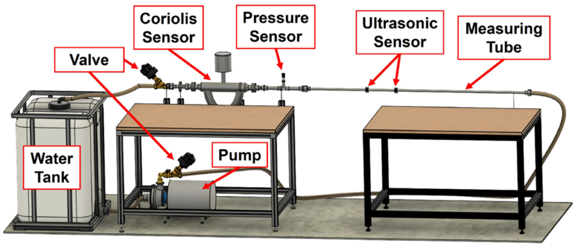

Fig. 6: Water test rig.

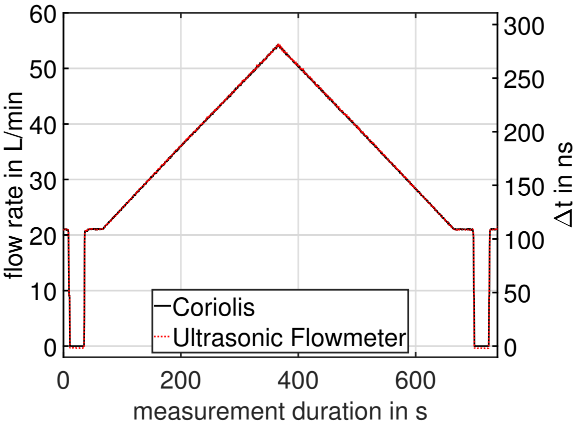

Fig. 7: Comparison of Coriolis and Ultrasonic Flow meter.

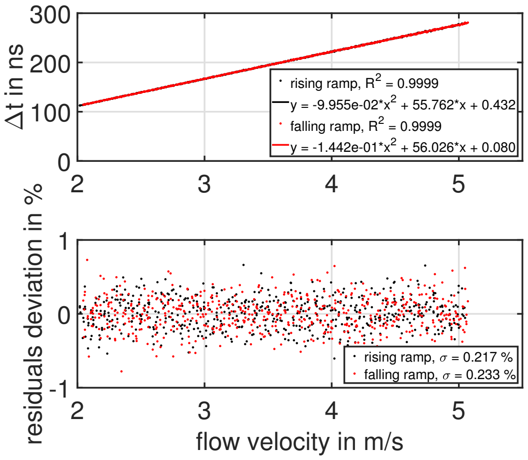

Fig. 8: Flow rate dependent signal shift.

As can be clearly seen in the figure, it is possible to achieve an almost perfect match between the Coriolis sensor and the ultrasonic flow sensor by appropriately scaling the right y-axis. It should be noted that the data had to be shifted by $-1.8\ \mathrm{ns}$ in the y-direction in order to achieve a match between the curves. This leads to a slight offset in the area without flow. The cause of this is not yet clear and is therefore not discussed further.

In Fig. 8 at the top, the determined signal transit time shift of the rising and falling ramp is plotted against the mean flow velocity determined from the flow rate and a 2nd-order polynomial regression was performed. The relative deviation of the residuals is shown below. From the linear term of the regression, a signal transit time shift comparable to the convection coefficient and dependent on the mean flow velocity can be determined. This is around $55.9\ \mathrm{ns}/(\mathrm{m}/\mathrm{s})$ and is therefore 2.5 times larger than a comparable lamb wave-based ultrasonic flow sensor with a V-path. It should be mentioned here that the resulting signal propagation time shift can be adjusted almost arbitrarily depending on the selected sensor distance. It is therefore possible to obtain a more compact sensor with a smaller distance or to increase the signal transit time shift and thus also the accuracy with a larger distance. This reduces the dependence on the pipe and fluid properties and thus opens up new design possibilities for ultrasonic flow sensors.
Although the significantly higher number of existing cylindrical modes compared to Lamb waves with a similar geometry represents a challenge in sensor development, it also opens up new possibilities with regard to disturbance compensation. Future investigations and experiments will have to show the scope of potential applications and the limits of cylindrical modes for ultrasonic flow measurement.

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References

[1] O. Fiedler. *Strömungs- und Durchflussmesstechnik*. München; Wien: Oldenbourg, 1992. 360 pp. ISBN: 3-486-22119-1.

[2] D. A. Kiefer, A. Benkert, and S. J. Rupitsch. “Transit Time of Lamb Wave-Based Ultrasonic Flow Meters and the Effect of Temperature”. In: *IEEE transactions on ultrasonics, ferroelectrics, and frequency control* 69.10 (Sept. 2022), pp. 2975–2983. DOI: 10.1109/TUFFC.2022.3201106.

[3] A. Backer et al. “NON-INVASIVE ULTRASONIC FLOW MEASUREMENT METHOD FOR THE DETECTION OF FLOW RATES IN THE MICROLITER RANGE”. In: *The 5th Conference on MicroFluidic Handling Systems (MFHS 2024)*. Munich, Germany, Feb. 21, 2024, pp. 29–32.

[4] *COMSOL Multiphysics®*. Version 6.1. Stockholm, Sweden. URL: www.comsol.com.

[5] M. Lowe and B. Pavlakovic. *DISPERSE - A System for Generating Dispersion Curves*. Version 2.0.20f. London, Nov. 14, 2019.