Fluid-coupled mechanical waveguides for ultrasonic sensing

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The Chair for Sensor Technology at FAU

FAU University of Erlangen-Nürnberg

- Supervisor: Prof. Stefan J. Rupitsch
- Colleague: Michael Ponschab

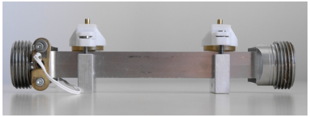
DIEHL Metering — Diehl Metering GmbH

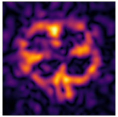
- Project partner

Location in Germany[1]

[1] Image modified from "NordNordWest".

Overview





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Flow metering market

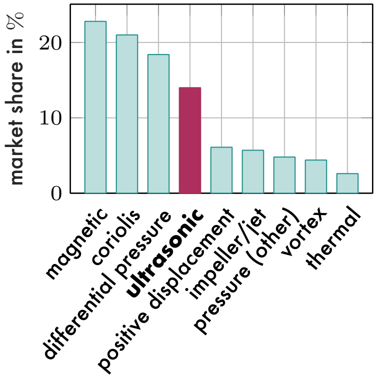
Water supply[1]

food industry[1]

Pipeline[1]

process monitoring[1]

global market share of meter types in 2015[2]



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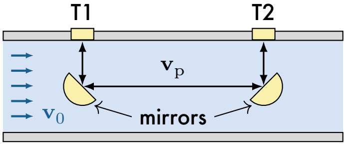
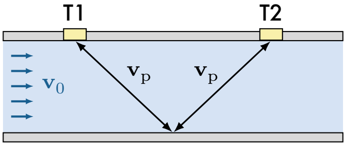
[2]Source: pixabay.com

[2]M. A. Linnert. "Energieeffiziente Felderzeugung für die magnetisch-induktive Durchflussmessung." Dissertation. Erlangen: University of Erlangen-Nürnberg, Mar. 2020.

Principle of transit-time ultrasonic flow metering

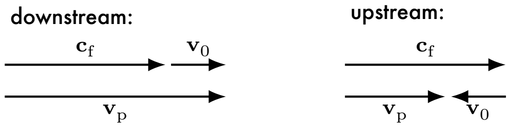


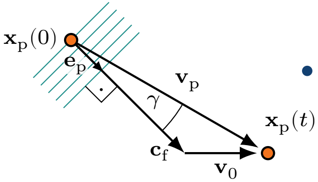
U-path



V-path

- wave speed c_f and flow velocity v_0 result in the ray velocity v_p

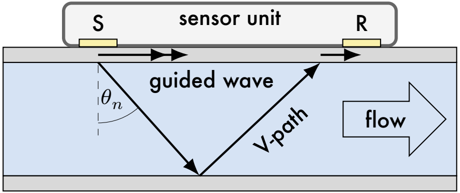




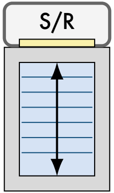
- change of propagation
  - → direction
  - → velocity v_p

Upstream-downstream difference in time of flight $\Delta\tau_\mathrm{p}$ (T2→T1 and T1→T2).

Concept: Lamb wave based flow meter



axial



transversal

advantages/disadvantages:

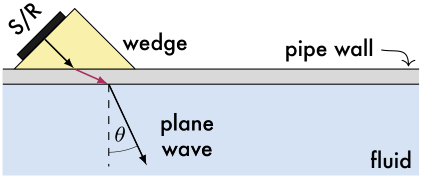
+ modular
+ no obstructions
+ no perforations
– interruption of process

challenges:

- transmission through the pipe wall
- temperature compensation

modeling of the proposed design

Mechanics of the pipe wall



desired

- conventional model
- strong simplification
- restricted θ:
  $\theta \leq 23°$ for steel-water
- weak transmission

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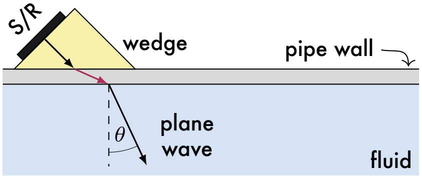
Mechanics of the pipe wall



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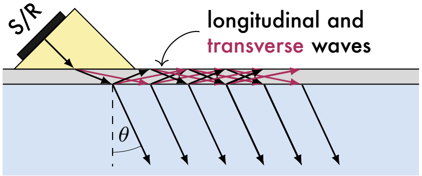

actual

- conventional model
- strong simplification
- restricted θ:
  $\theta \leq 23°$ for steel-water
- weak transmission

- **guided waves**
- resonances of the pipe wall
- strong transmission

in the following:

basis for modeling

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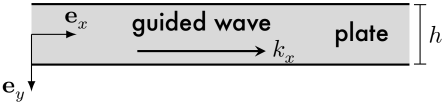
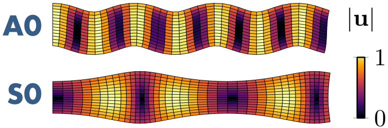
Lamb waves: guided waves in a free plate



cross-section of a plate



A0: anti-symmetric, **S0**: symmetric

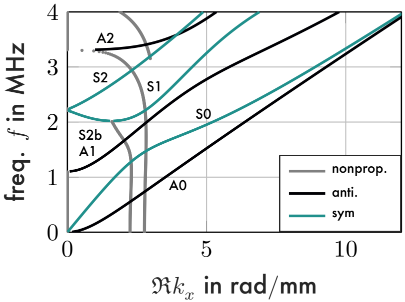
- harmonic plane wave ansatz for the particle **displacements**:

$$\mathbf{u}(x, y, t) = \mathbf{u}(y)\, \mathrm{e}^{\mathrm{i}(k_x x - \omega t)}$$

- eigenvalue problem for $\mathbf{u}(y)$, k_x:

Dispersion

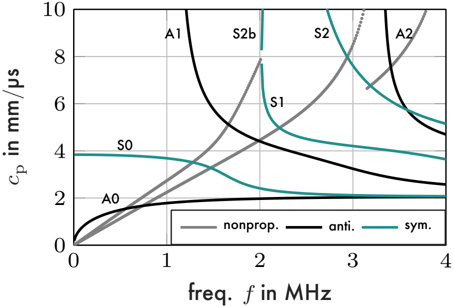
$k_x = k_x(\omega)$ nonlinear



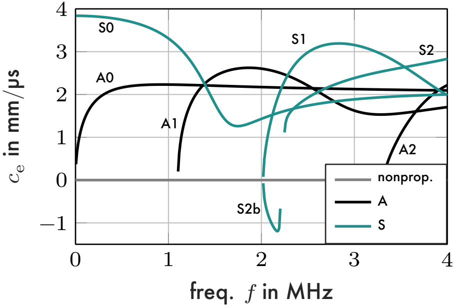
brass plate, 1 mm

Wave velocities

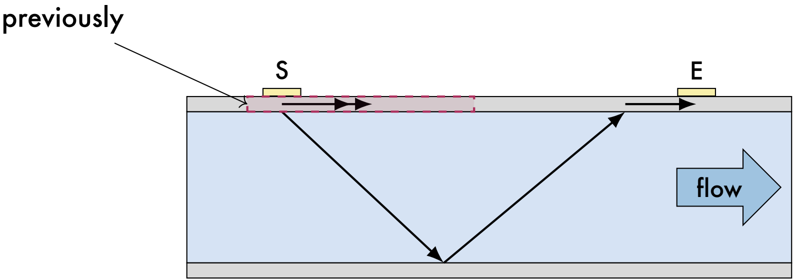
Phase velocities



Energy velocities



Next: fluid-structure interaction



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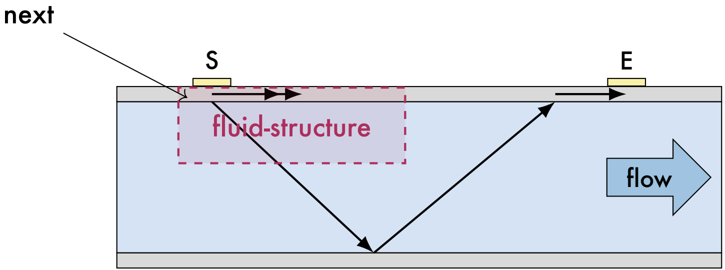
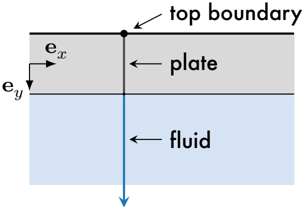


Models for a plate-fluid system

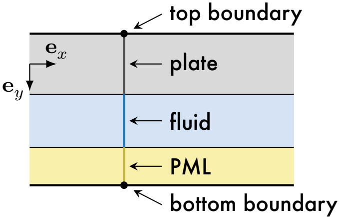
Different models to resolve $\mathbf{u}(y)$:

Full model:



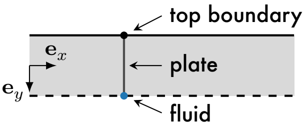
- continuous spectrum
  $\rightarrow$ integral as solution

Truncated model:



- discrete spectrum
- includes parameters that are not related to the physics

Open plate model:



- discrete spectrum
- plate-fluid resonances

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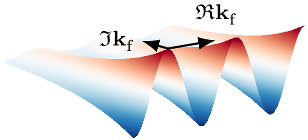
Quasi-guided waves

a-priori:

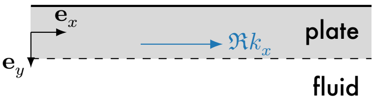
inhomogeneous plane wave in fluid



- complex wave vector: $\mathbf{k}_\mathrm{f} = \begin{bmatrix} k_x \\ k_y \end{bmatrix}$
- dispersion relation:

$$\mathbf{k}_\mathrm{f} \cdot \mathbf{k}_\mathrm{f} = \frac{\omega^2}{c_\mathrm{f}^2} \in \mathbb{R} \quad \Rightarrow \quad \Re\mathbf{k}_\mathrm{f} \perp \Im\mathbf{k}_\mathrm{f}$$

- wave vectors:



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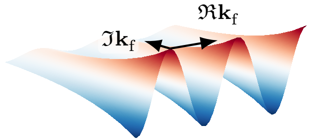

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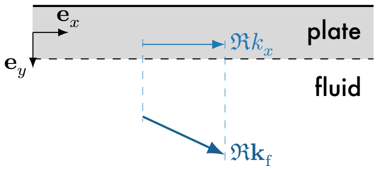

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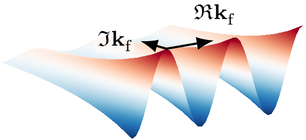

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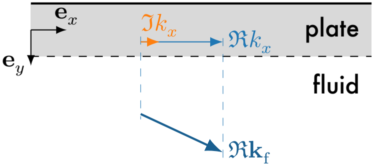

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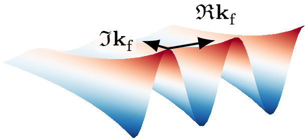

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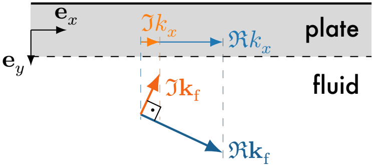

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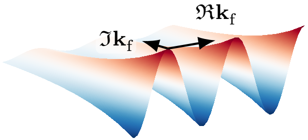

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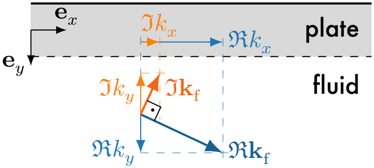

→ where: $k_y(k_x) = \sqrt{\frac{\omega^2}{c_\mathrm{f}^2} - k_x^2}$

Quasi-guided waves

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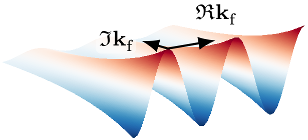

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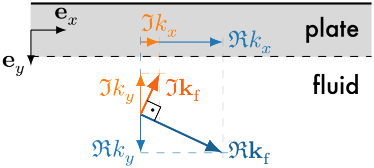

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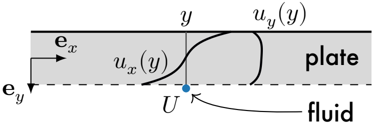
- displacement field:



→ additional unknown: **amplitude** U

Solving the quasi-guided wave problem[3]

- determine:
  - $\rightarrow$ eigenfunctions $[u_x(y), u_y(y), U]^\top$
  - $\rightarrow$ eigenvalues k_x

$\Rightarrow$ nonlinear eigenvalue problem (EVP)

- involving $k_y(k_x) = \sqrt{\frac{\omega^2}{c_\mathrm{f}^2} - k_x^2}$

[3] D. A. Kiefer et al. "Calculating the full leaky Lamb wave spectrum with exact fluid interaction." In: The Journal of the Acoustical Society of America 145.6 (June 2019), pp. 3341–3350.

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Idea:

- **linear** in new variable γ:

$$k_x \stackrel{\text{def}}{=} \frac{\kappa_\mathrm{f}}{2}(\gamma + \gamma^{-1}) \quad \Rightarrow \quad k_y = \pm\frac{\kappa_\mathrm{f}}{2\mathrm{i}}(\gamma - \gamma^{-1})$$

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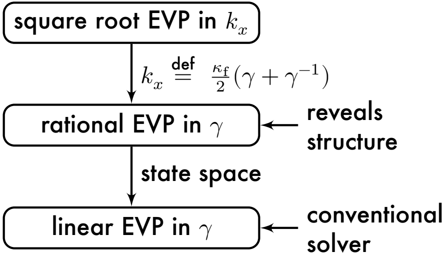

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- ✓ reliable and efficient
- ✓ exact fluid-structure interaction
- ✓ uniquely obtain $[k_x, k_y]$

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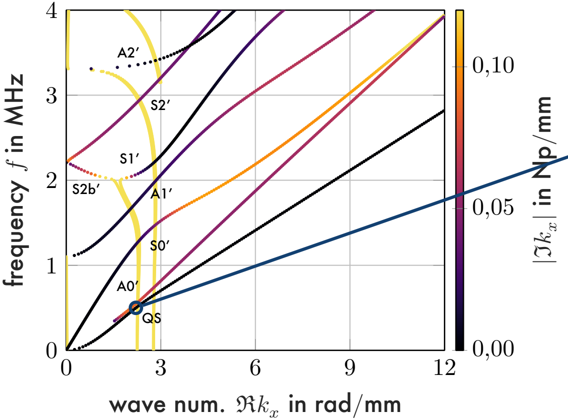
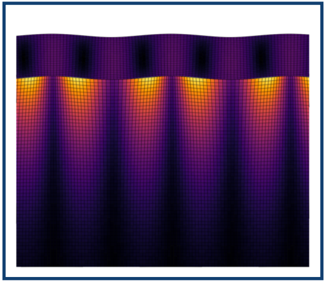
Trapped and leaky wave solutions

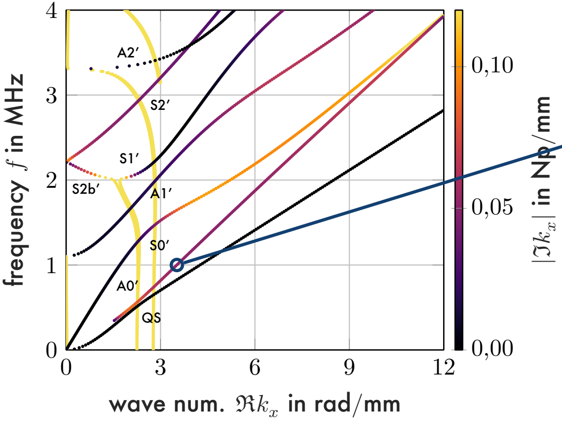


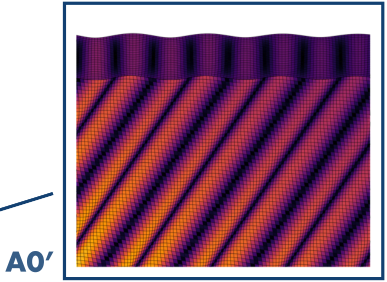
QS



- trapped wave
- transport of energy along the plate

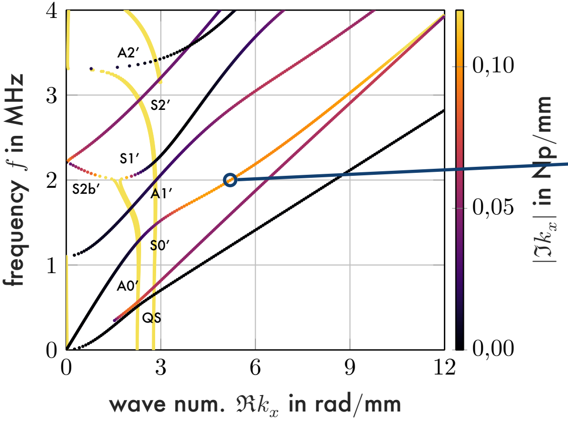
Trapped and leaky wave solutions

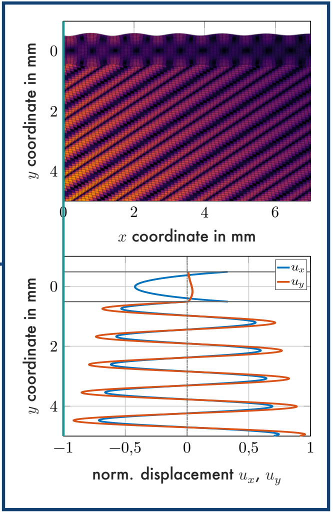




- leaky wave
- radiation into the fluid

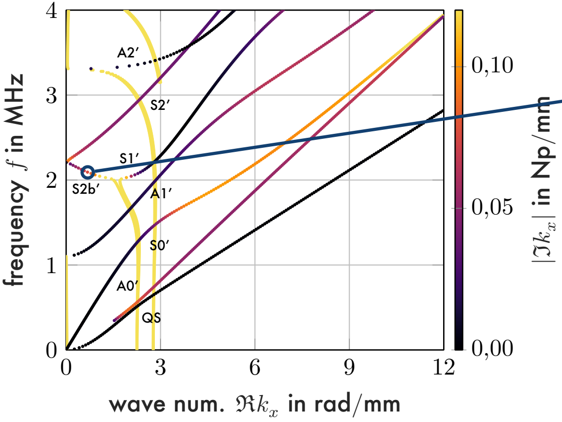
Trapped and leaky wave solutions

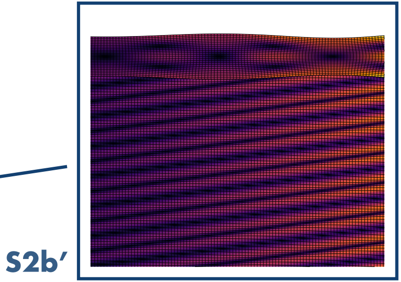




S0′

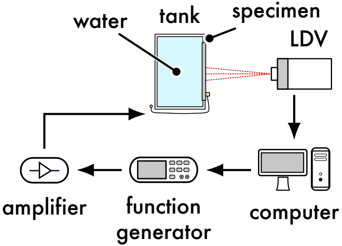
Trapped and leaky wave solutions

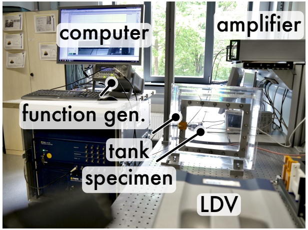


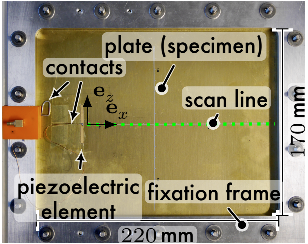


- leaky wave
- radiation "to the back"
- Does not diverge with distance to the plate.

Measurement of dispersion curves

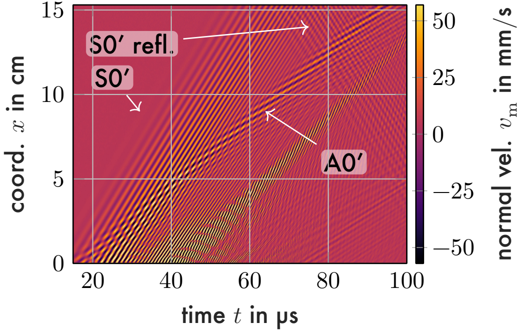




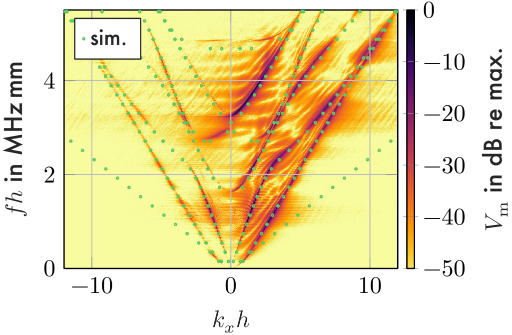


- transducer:
  bonded piezoelectric element
- excitation: chirp with
  $D = 100\,\mu s$, $B = 3.8$ MHz
- measurement: heterodyne interferometer
- scan of the center line

Measurement results: steel 1.5 mm, water



velocity field



reciprocal space

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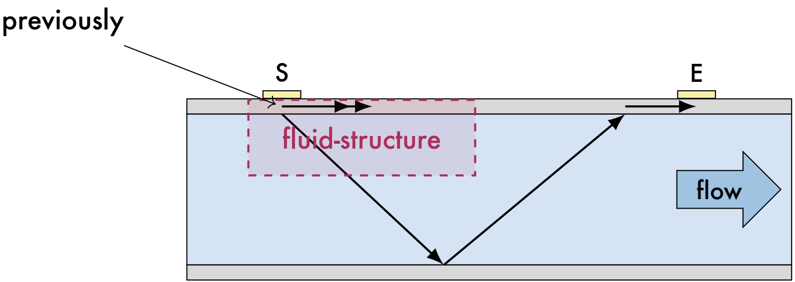
Next: sound-flow interaction



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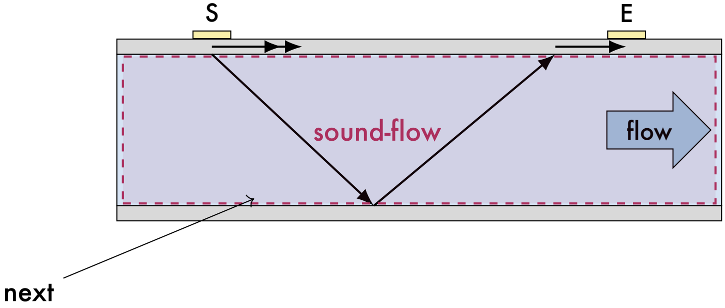
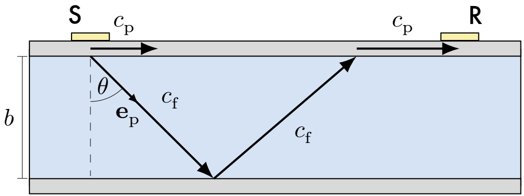
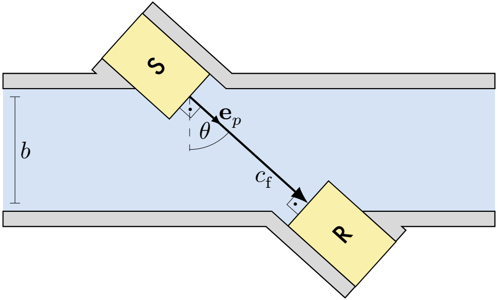


Time of flight comparison of flow meters





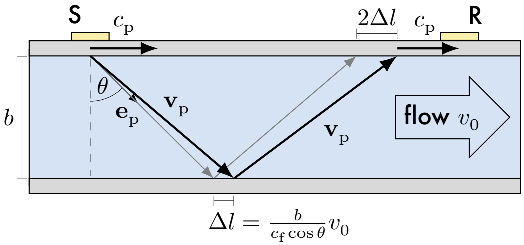
- **constant** transit time
- **change** of the path length Δl

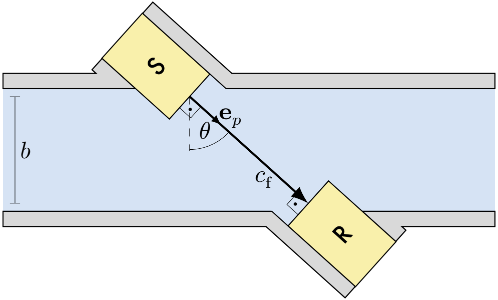
$$\Delta\tau_\mathrm{p} = \frac{4b}{c_\mathrm{f}\cos\theta}\frac{v_0}{c_\mathrm{p}}$$

- **constant** path length (almost)
- **change** of the velocity $c_\mathrm{f} \to \mathbf{v}_\mathrm{p}\cdot\mathbf{e}_\mathrm{p}$

$$\Delta\tau_\mathrm{p} = \frac{4b}{\cos\theta}\frac{v_0\sin\theta}{(c_\mathrm{f}^2 - v_0^2\sin^2\theta)}$$

Time of flight comparison of flow meters





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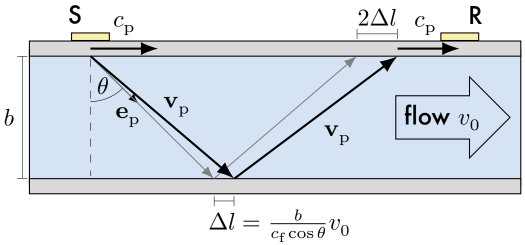

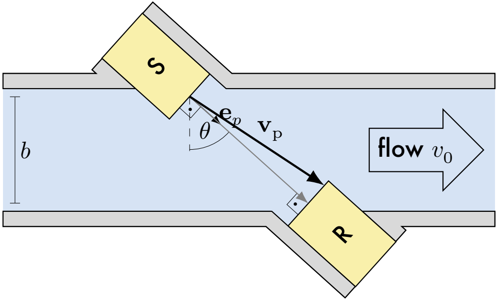

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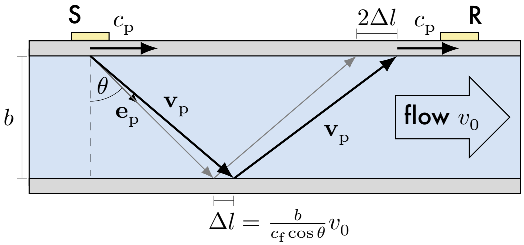
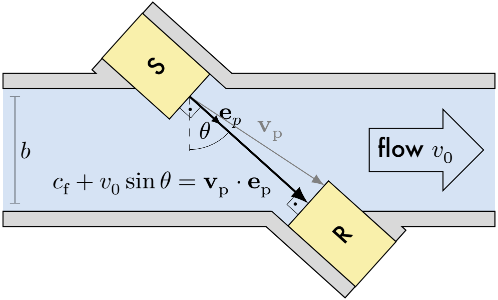
Time of flight comparison of flow meters





- **constant** transit time
- **change** of the path length Δl

- **constant** path length (almost)
- **change** of the velocity $c_f \to \mathbf{v}_p \cdot \mathbf{e}_p$

$$\Delta\tau_p = \frac{4b}{c_f \cos\theta} \frac{v_0}{c_p}$$

dev.: $\frac{v_0^2}{c_p^2} \approx 0.1\,‰$ $\leftrightarrow$

$$\Delta\tau_p = \frac{4b}{\cos\theta} \frac{v_0 \sin\theta}{(c_f^2 - v_0^2 \sin^2\theta)}$$

$+$ simpler $+$ more general

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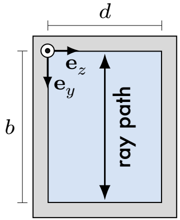
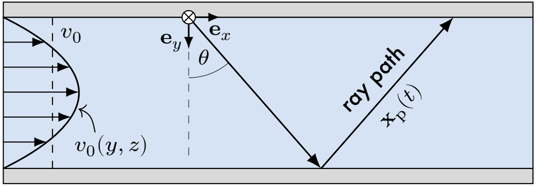
Determining the flow rate Q



pipe: transversal section



pipe: axial section

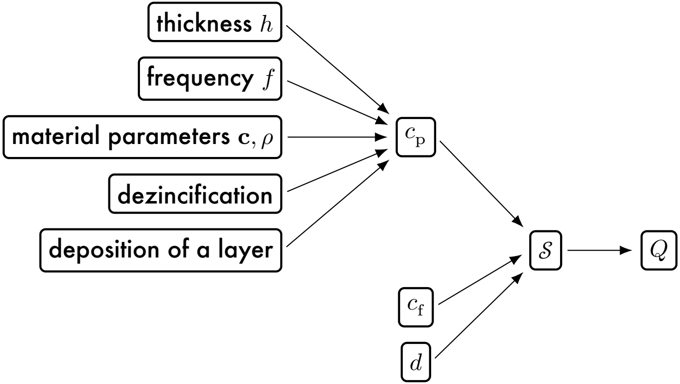
flow rate: $$Q \overset{\text{def}}{=} \int_0^d \int_0^b v_0(y,z)\,\mathrm{d}y\,\mathrm{d}z = Kbdv_0 = \underbrace{\frac{1}{4}Kdc_\mathrm{f}c_\mathrm{p}\cos\theta}_{\text{sensitivity } \mathcal{S}}\Delta\tau_\mathrm{p}$$

Measurement errors due to:

- $\Delta\tau_\mathrm{p}$: electronics + signal processing
- $\mathcal{S}$: **ultrasonic system**

Measurement error diagram

Possible errors due to sensitivity: $\mathcal{S} = \frac{1}{4} K d c_\mathrm{f} c_\mathrm{p} \cos\theta(c_\mathrm{p}, c_\mathrm{f})$



- Perturbation theory[4]: analytical expressions for effect on c_p.

[4] B. A. Auld. Acoustic Fields and Waves in Solids. 2nd ed. Vol. 2. Krieger Publishing Company, 1990. 878 pp.

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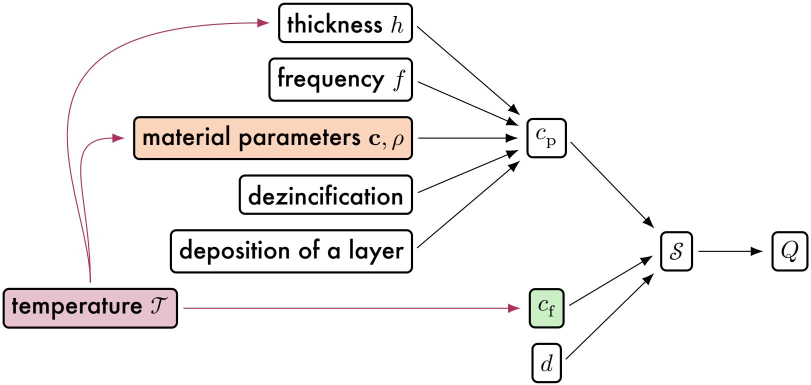

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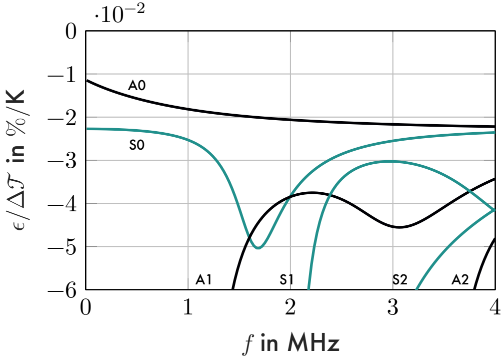
Effect of temperature $\mathcal{T}$

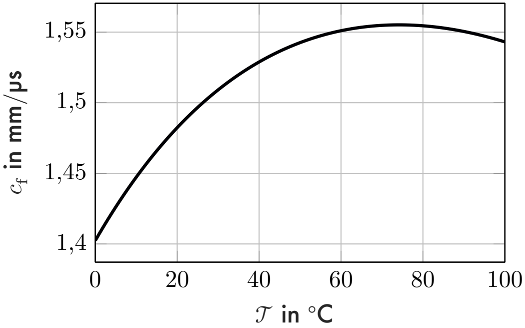
pipe material: $c_\mathrm{p}(\mathcal{T}) = (1+\epsilon)c_\mathrm{p}$

- with $\epsilon = \frac{1}{2}\frac{c_\mathrm{p}}{c_\mathrm{e}}\frac{\partial E}{\partial \mathcal{T}}\frac{\Delta\mathcal{T}}{E}$



water: $c_\mathrm{f}(\mathcal{T})$

- polynomial fit to experimental data[5]

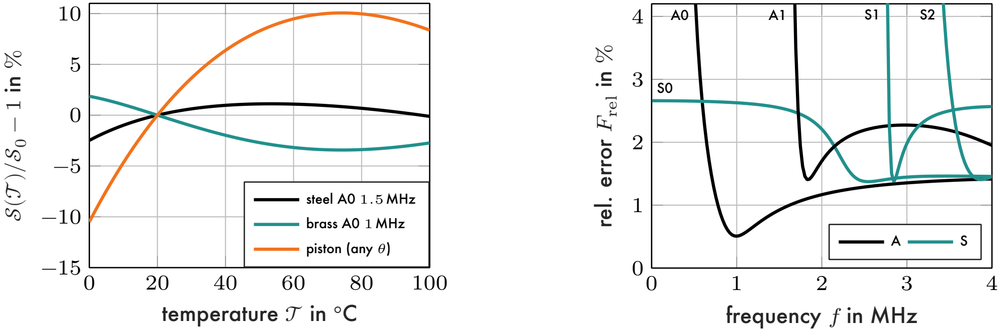


[5] N. Bilaniuk and G. S. K. Wong. "Speed of sound in pure water as a function of temperature." In: The Journal of the Acoustical Society of America 93.3 (Mar. 1, 1993), pp. 1609–1612.

Effect of temperature $\mathcal{T}$ on the flow meter

piston: $\mathcal{S} \sim c_\mathrm{f}^2(\mathcal{T}) \leftrightarrow$ **Lamb:** $\mathcal{S} \sim c_\mathrm{f}(\mathcal{T})\sqrt{c_\mathrm{p}^2(\mathcal{T}) - c_\mathrm{f}^2(\mathcal{T})}$

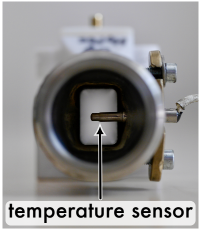
$$F_\mathrm{rel} \overset{\mathrm{def}}{=} \frac{1}{\mathcal{S}_0}\sqrt{\frac{1}{\mathcal{T}_2 - \mathcal{T}_1}\int_{\mathcal{T}_1}^{\mathcal{T}_2} [\mathcal{S}(\mathcal{T}) - \mathcal{S}_0]^2 \,\mathrm{d}\mathcal{T}}$$

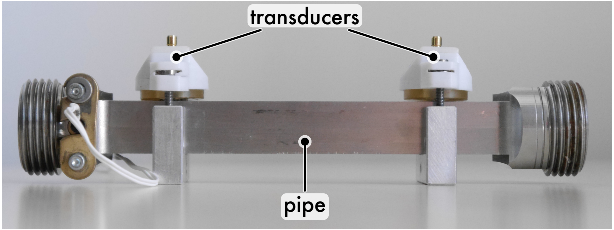


- piston transducer: $F_\mathrm{rel} = 7.8\,\%$

Lamb-wave based flow meters exhibit less cross-sensitivity to temperature.

Prototype of the flow meter





flow meter prototype[6]

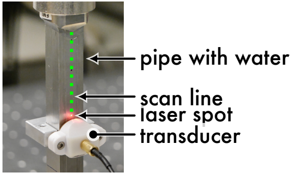
- steel pipe, $1.5\,$mm wall thickness
- piezoelectric Lamb wave transducers

next:

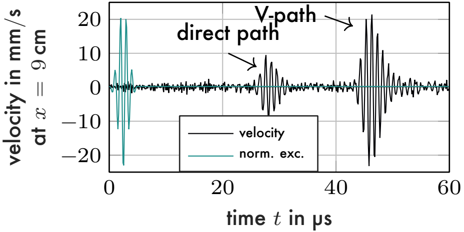
- validated model:
  1. vibrometer measurement $\rightarrow$ pipe wall mechanics
  2. transmission measurements $\rightarrow$ time of flight

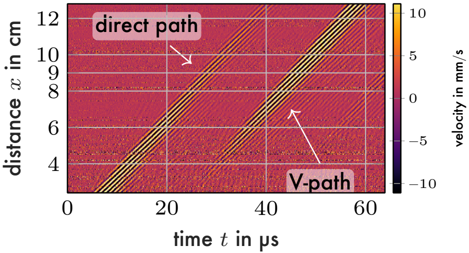
[6] Designed and fabricated by Diehl Metering GmbH.

1 Vibrometer measurements

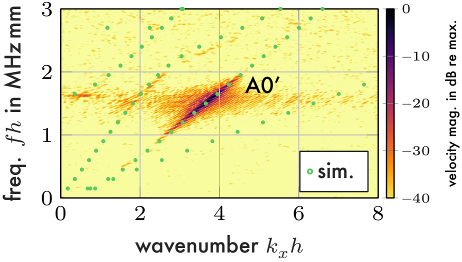


laboratory setup



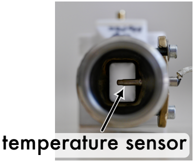


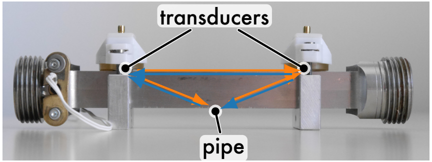
space: x-t



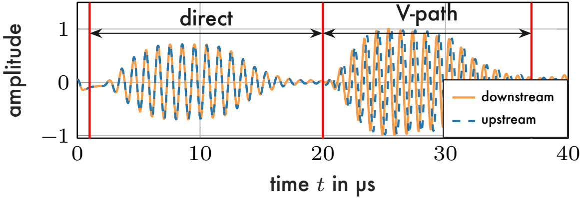
reciprocal space: f-k_x

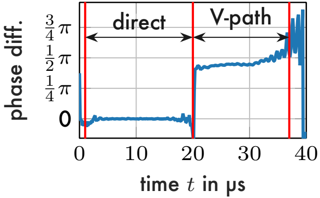
2 Transmission measurements





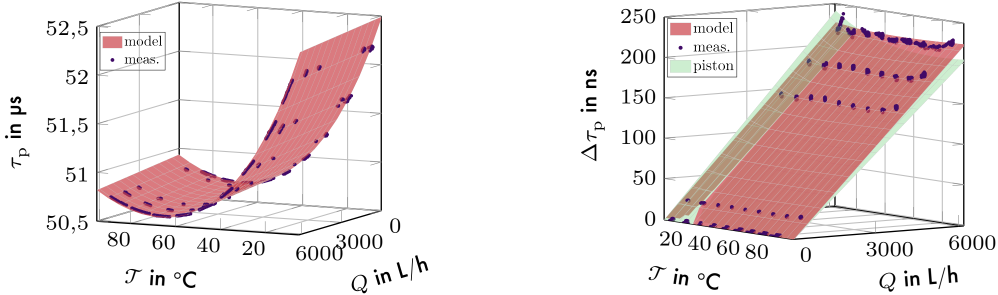
- 7665 measurements at controlled and supervised parameter values[7]:
  - → flow rate Q_{nom}: 6.4, 63, 630, 4000, 5000, and 6000 L/h
  - → temperature $\mathcal{T}_{\mathrm{nom}}$: $10\,$°C – $90\,$°C in steps of $10\,$°C
  - → reference measurements Q_{ref} and $\mathcal{T}_{\mathrm{ref}}$





[7] Raw data obtained by Diehl Metering GmbH.

2 Validation of the time-of-flight model



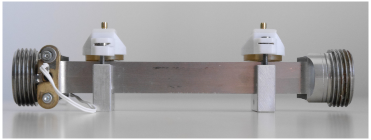
downstream

upstream-downstream difference

- model: time of flight $\tau_p(\mathcal{T})$
- model: $\Delta\tau_p = \mathcal{S}^{-1}(\mathcal{T})Q$

- $\frac{\partial E}{\partial \mathcal{T}}$ fitted to data
  $\rightarrow \approx 10\,\%$ deviation from material datasheet

Conclusion of Lamb wave based flow meters



- modeling with (leaky) guided waves:
  - $\rightarrow$ rapidly converging discrete basis
  - $\rightarrow$ including the effect of flow and temperature
  - $\rightarrow$ simple to invert
  - $\rightarrow$ reveals an intrinsic passive compensation to temperature

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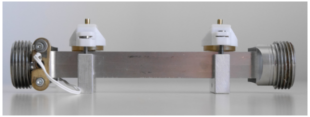
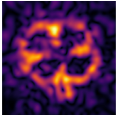
Overview





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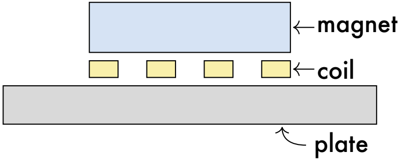
Electromagnetic Acoustic Transducers (EMATs)[8]



coil on flexible PCB

- current: $20\,\mathrm{A}$
- impedance matching network
- contact-less

[8] L. Vogl. "Simulation-based design, implementation and verification of an electromagnetic acoustic transducer for generation of Lamb waves." Bachelor Thesis. University of Erlangen-Nürnberg, Apr. 2018.

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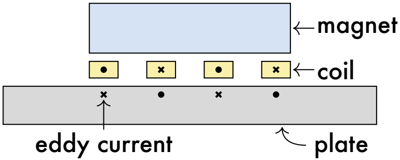

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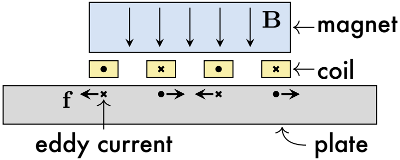

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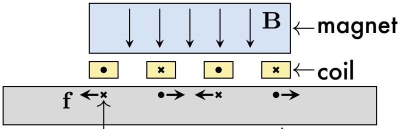

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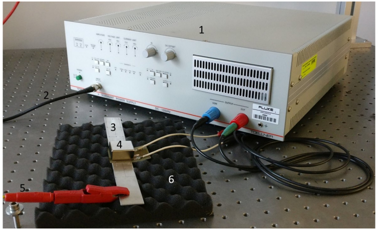
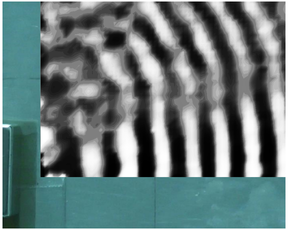


laboratory setup



vibrometer measurement

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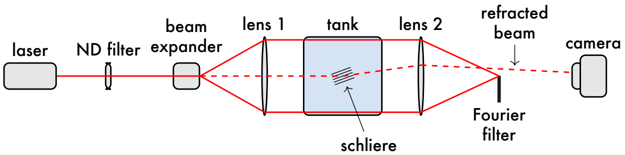
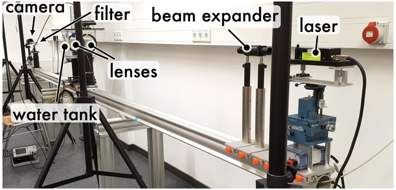
Schlieren photography of ultrasonic phenomena[9,10]



Schlieren photography system



laboratory setup

[9] K. Schmid. "Schlieren-optical imaging of the radiation of plate waves into a fluid." Bachelor Thesis. University of Erlangen-Nürnberg, Oct. 2018.

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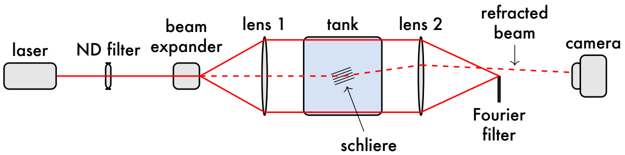

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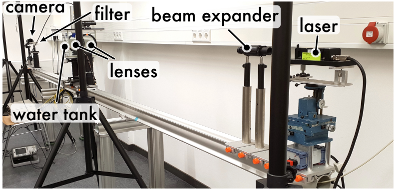

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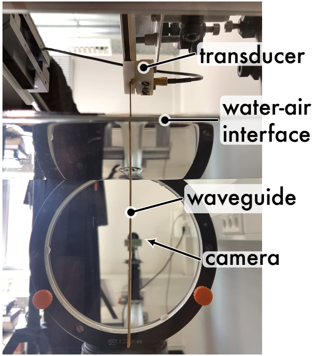

radiating waveguide

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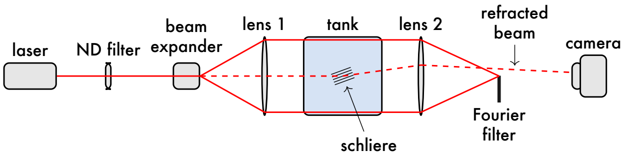
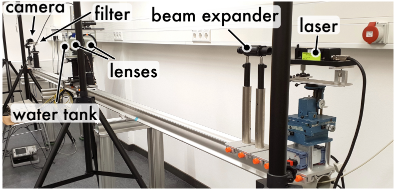
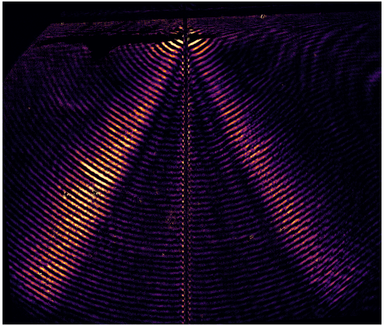


Schlieren photography system



laboratory setup



Schlieren image: A0, 1 MHz, 1 mm brass

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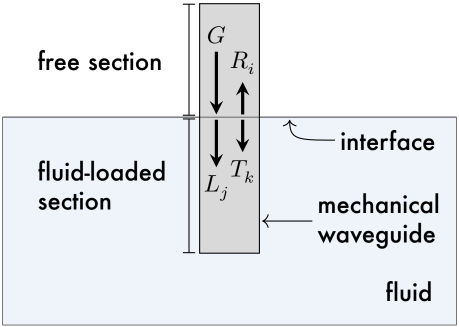
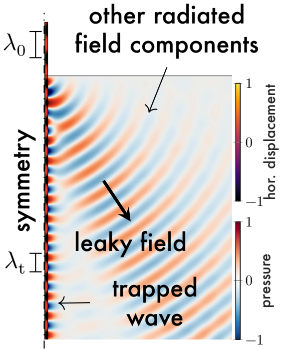
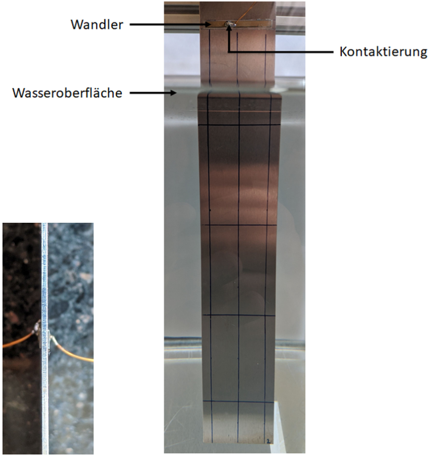
Immersed stick: mode conversion

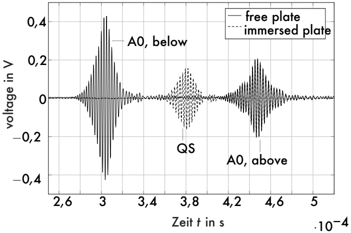




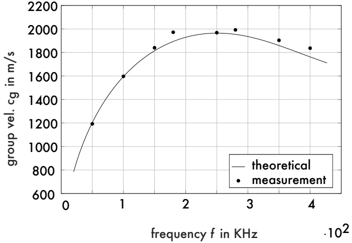
FE computation: PMMA-water

Dip-stick sensor[11]





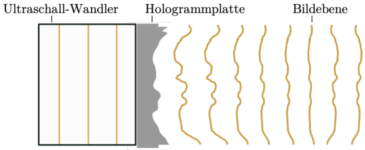
received signals



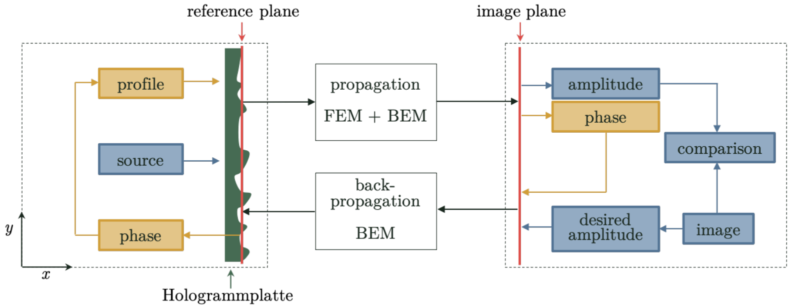
measurement of group velocity

[11] L. Vogl. "Measurement of fluid properties with the quasi-Scholte plate mode." Master Thesis. University of Erlangen-Nürnberg, Aug. 2020.

Holography[12,13]



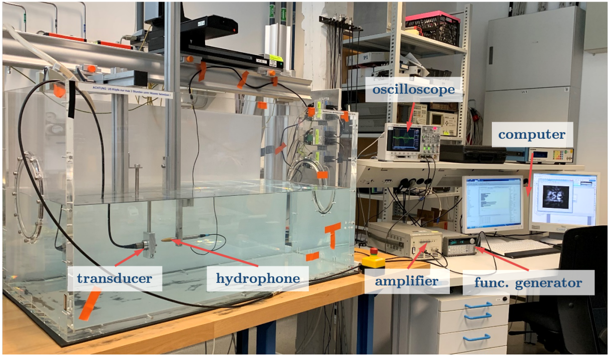
- Iterative Angular Spectrum Approach (Gerchberg-Saxton):
  - → Fourier acoustics
  - → only longitudinal waves



[12] J. Freitag. "Design, implementation and verification of acoustic holograms considering full solid mechanics." Master Thesis. University of Erlangen-Nürnberg, Sept. 2020.

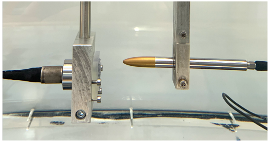
[13] C. Ittner. "Design, fabrication and verification of an acoustic hologram." Master Thesis. University of Erlangen-Nürnberg, July 2019.

Hologram measurements[14]



laboratory setup

- 6 hours measurement:



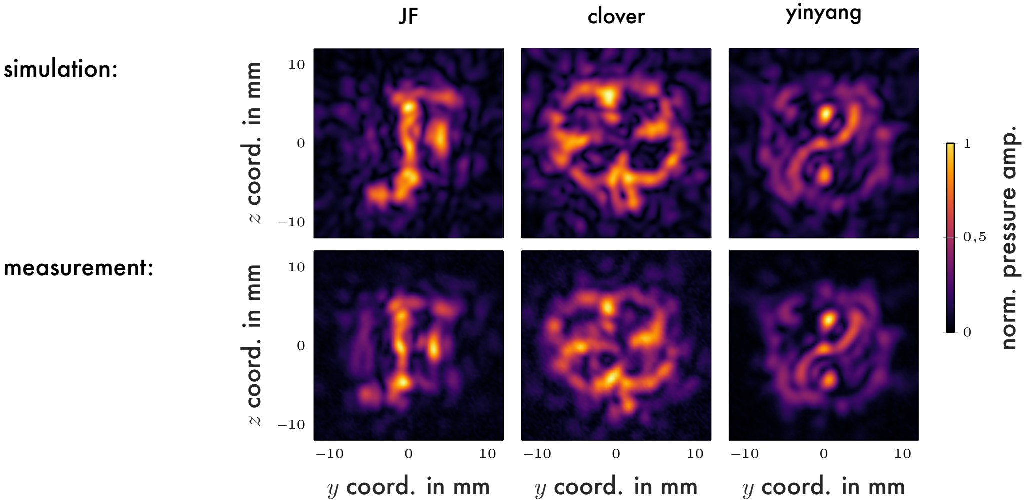
scanning hydrophone

- stereolithography:

holographic plate

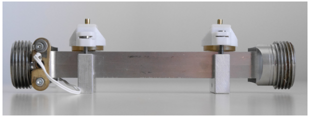
[14] J. Freitag. "Design, implementation and verification of acoustic holograms considering full solid mechanics." Master Thesis. University of Erlangen-Nürnberg, Sept. 2020.

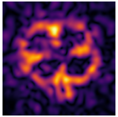
Measured holograms[15]



[15] J. Freitag. “Design, implementation and verification of acoustic holograms considering full solid mechanics.” Master Thesis. University of Erlangen-Nürnberg, Sept. 2020.

Overview





Remarks on modeling with quasi-guided/leaky waves

- dip-stick sensor
  $\rightarrow$ conversion coefficients
- sensitivity analysis with leaky waves
  $\rightarrow$ perturbation theory
- nonspecular reflection with leaky waves
- energy velocity c_e

Quasinormal mode (QNM) theory of quasi-guided waves needed[16]

[16] E. S. C. Ching et al. "Quasinormal-mode expansion for waves in open systems." In: Reviews of Modern Physics 70.4 (Oct. 1, 1998), pp. 1545–1554.

Outlook

- modeling with leaky Lamb waves
  → normalmode theory
- Zero-Group-Velocity resonances (Claire Prada)
  → modeling
  → leakage
- waves in fluid-coupled resonators (Fabrice Lemoult)

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Outlook

- modeling with leaky Lamb waves
  - → normalmode theory
- Zero-Group-Velocity resonances (Claire Prada)
  - → modeling
  - → leakage
- waves in fluid-coupled resonators (Fabrice Lemoult)

Merci beaucoup pour votre attention!

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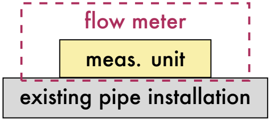
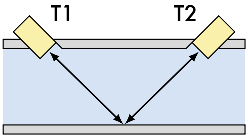
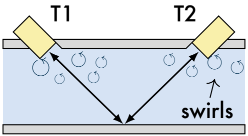
Flow meter designs



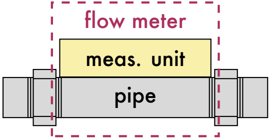
clamp on



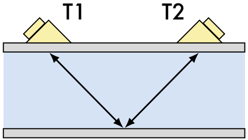
invasive



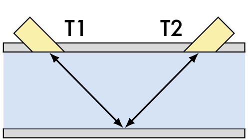
intrusive



inline



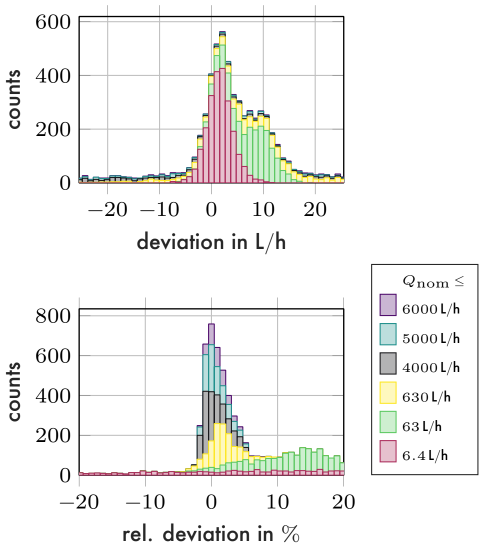
non-invasive



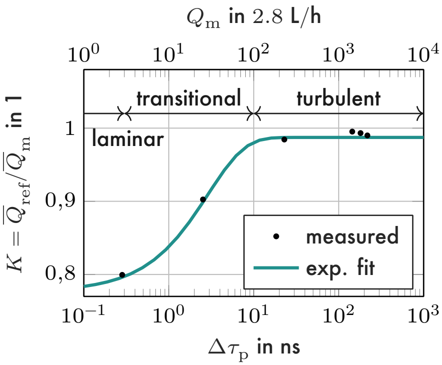
non-intrusive

here: inline, non-invasive, non-intrusive

Determination of the flow rate Q: model inversion



$$Q_{\mathrm{m}} = \mathcal{S}(\mathcal{T})\Delta\tau_{\mathrm{p}}$$



hydrodynamic correction factor K as suggested by the acquired data

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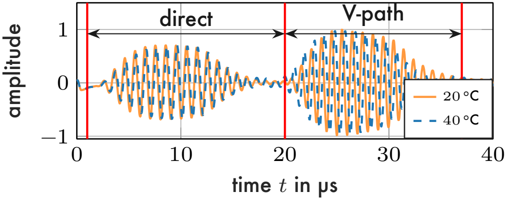
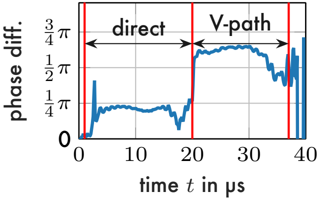
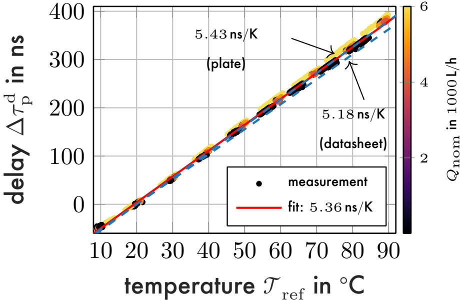
Temperature determination from direct path signal







- from sensitivity analysis:

$$\Delta\tau_{\mathrm{p}}^{\mathrm{d}}(\mathcal{T}) \approx -\frac{D}{2c_{\mathrm{e}}}\frac{\partial E}{\partial \mathcal{T}}\frac{\Delta\mathcal{T}}{E}$$

- uncertainty ≈ 2 K
- avoid temperature sensor

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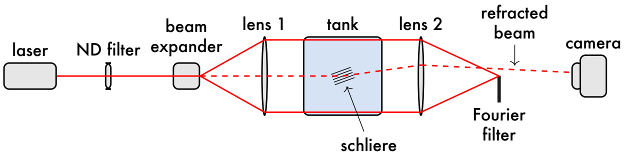
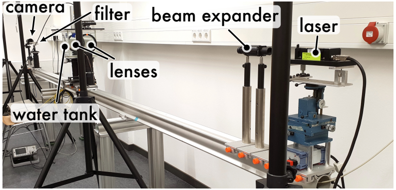
Schlieren photography of ultrasonic phenomena[17,18]



Schlieren photography system

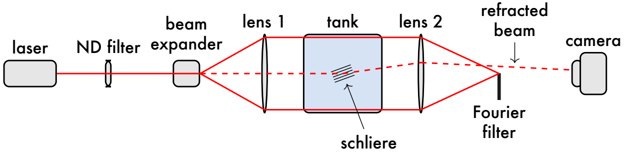


laboratory setup

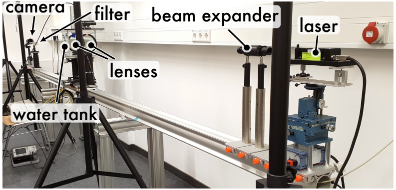
[17] K. Schmid. "Schlieren-optical imaging of the radiation of plate waves into a fluid." Bachelor Thesis. University of Erlangen-Nürnberg, Oct. 2018.

[18] S. Sivanesan. "Simulation and utilization of spatial light modulators for schlieren-optical imaging of ultrasound." Master Thesis. University of Erlangen-Nürnberg, Aug. 2020.

Schlieren photography of ultrasonic phenomena[17,18]



Schlieren photography system



laboratory setup

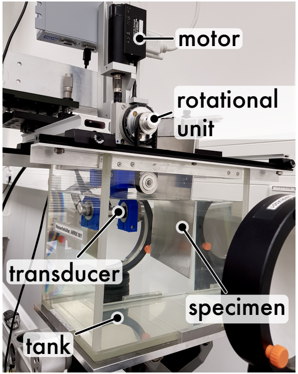


plate insonification

[17] K. Schmid. "Schlieren-optical imaging of the radiation of plate waves into a fluid." Bachelor Thesis. University of Erlangen-Nürnberg, Oct. 2018.

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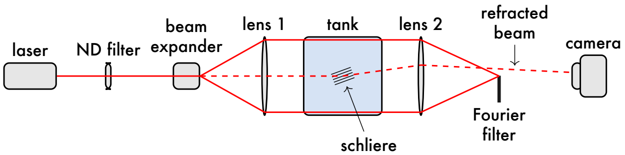
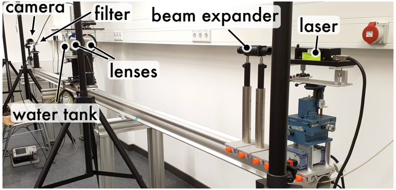
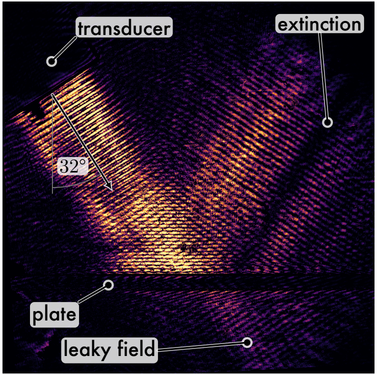
Schlieren photography of ultrasonic phenomena[17,18]



Schlieren photography system



laboratory setup

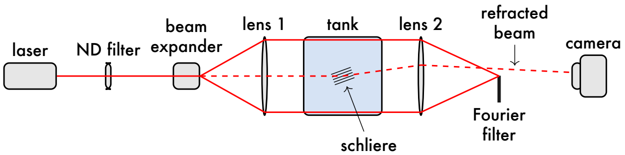


nonspecular reflection:
A0, 1 MHz, 3 mm steel

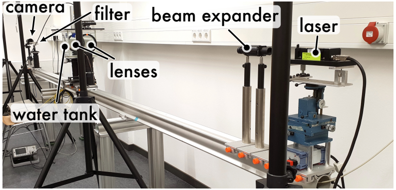
[17] K. Schmid. "Schlieren-optical imaging of the radiation of plate waves into a fluid." Bachelor Thesis. University of Erlangen-Nürnberg, Oct. 2018.

[18] S. Sivanesan. "Simulation and utilization of spatial light modulators for schlieren-optical imaging of ultrasound." Master Thesis. University of Erlangen-Nürnberg, Aug. 2020.

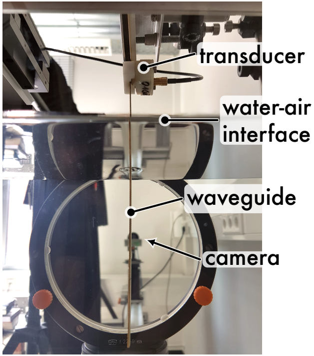
Schlieren photography of ultrasonic phenomena[17,18]



Schlieren photography system



laboratory setup



radiating waveguide

[17] K. Schmid. "Schlieren-optical imaging of the radiation of plate waves into a fluid." Bachelor Thesis. University of Erlangen-Nürnberg, Oct. 2018.

[18] S. Sivanesan. "Simulation and utilization of spatial light modulators for schlieren-optical imaging of ultrasound." Master Thesis. University of Erlangen-Nürnberg, Aug. 2020.

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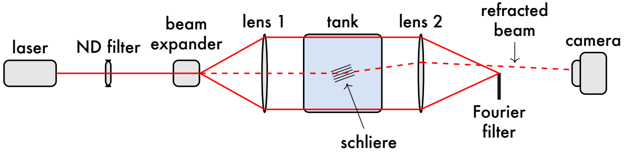
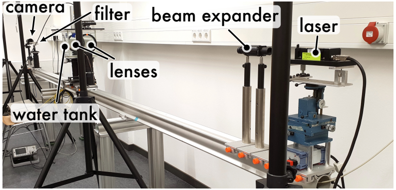
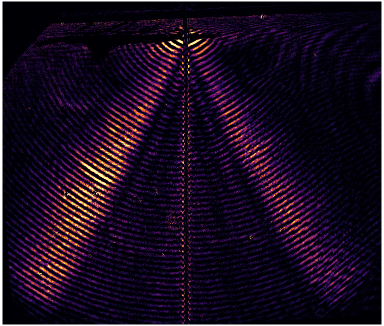


Schlieren photography system



laboratory setup



Schlieren image: A0, 1 MHz, 1 mm brass

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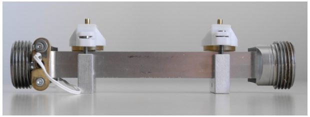
[17] K. Schmid. "Schlieren-optical imaging of the radiation of plate waves into a fluid." Bachelor Thesis. University of Erlangen-Nürnberg, Oct. 2018.

[18] S. Sivanesan. "Simulation and utilization of spatial light modulators for schlieren-optical imaging of ultrasound." Master Thesis. University of Erlangen-Nürnberg, Aug. 2020.

Conclusion of Lamb wave based flow meters



+ non-invasive configuration
  – influenced by the pipe wall mechanics
- modeling with (leaky) guided waves: rapidly converging discrete basis
  + handles the "structure borne" ultrasound
  + simple to invert model of the flow meter
  + insensitive to actual transducer
  → nonlinear eigenvalue problem reliably solved by change of variable

analysis of

- ultrasonic convection: different to piston transducer meters → beam displacement is sensed
- pipe: uncertainty and aging
- scaling and dezincification
- temperature behavior:
  + **intrinsic passive compensation** (guided waves ↔ fluid)
  + pipe material is relevant (design freedom)
  – hydrodynamic correction factor depends on temperature

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