Last lecture

- Measurement of volume flow rate
  - Differential pressure flowmeters
  - Mechanical flowmeters
  - Vortex flowmeters
- Measurement of mass flow
- Measurement of “tricky flows"

Today’s menu

- Ultrasonic measurement systems
- What is ultrasound?
- What are the main properties we can measure?
- Application examples

Ultrasonic measurement systems

What is ultrasound?

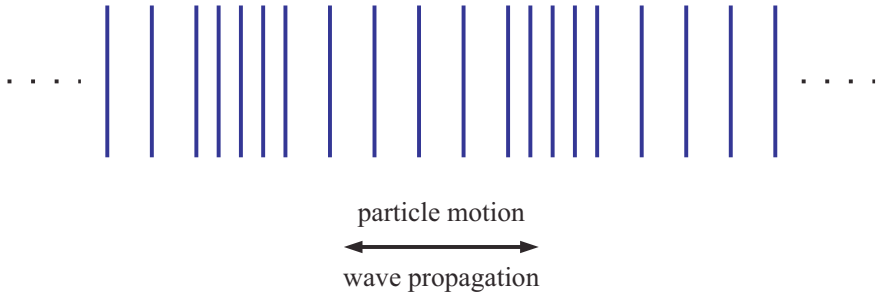
Acoustics may be defined as the *generation*, *transportation*, and *reception* of energy in the form of vibrational waves.

The sound propagation arises from internal elastic forces between atoms or molecules, when they are displaced from their equilibrium.

Ultrasound is defined as sound of frequencies above the audible range, that is above 20 kHz.

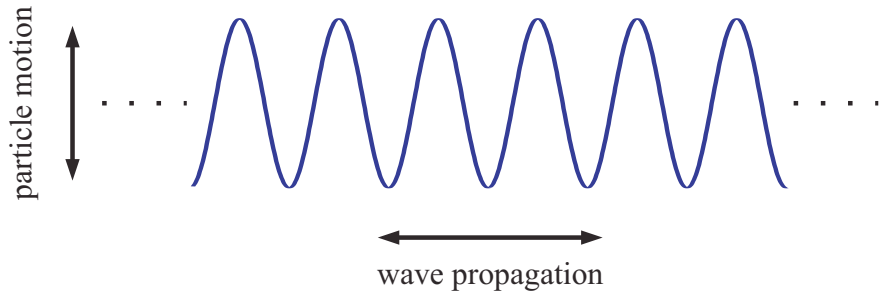
What is Ultrasound (cont’d...)?

Compression waves: Particle displacement and wave propagation in same direction.



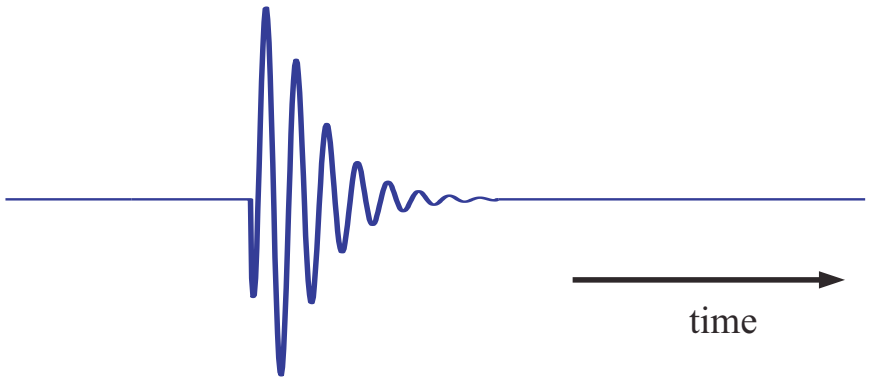
What is Ultrasound (cont'd...)?

Transversal waves: Particle displacement normal to wave propagation.



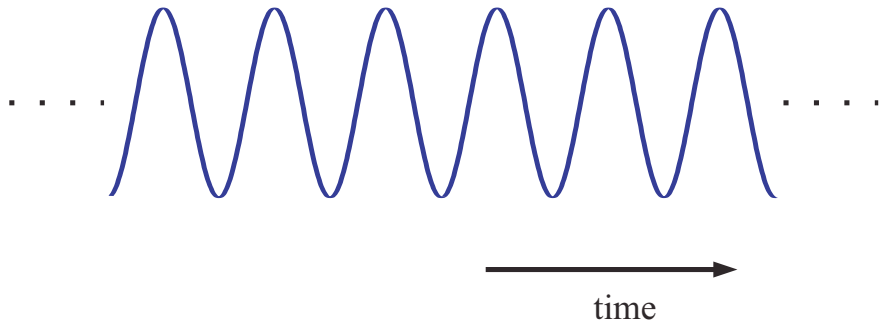
What is Ultrasound (cont'd...)?

We differ between **pulsed** sound



What is Ultrasound (cont'd...)?

...and **continuous**-wave ultrasound



Reflection and Transmission

When a sound wave encounters a boundary between two different materials, part is reflected and part is transmitted.

The reflection coefficient (number between 0 and 1) is defined as

$$R_{12} = \frac{z_2 - z_1}{z_1 + z_2},$$

where z_1 and z_2 are the acoustic impedances of medium 1 and 2, respectively.

This means that the amplitude of the reflected wave is $A_0 \cdot R_{12}$, where A_0 is the amplitude of the incident wave.

Reflection and Transmission (cont'd...)

The acoustic impedance of a material is given by:

$$z = \rho \cdot c,$$

where ρ is the density and c is the speed of sound. The acoustic impedance is measured in Pa·s/m.

Attenuation

When a sound wave propagates through a medium, its is also attenuated with distance, often modeled as:

$$A_1 = A_0 e^{-\alpha x},$$

where x is the propagation distance, α is the attenuation coefficient, and

A_0 is the amplitude of the transmitted wave.

What can we measure?

- From the received sound waves we can directly measure attenuation (damping) and speed of sound, as a function of wavelength (frequency).
- From attenuation and speed of sound we can calculate various properties, such as:
  - Reflection and transmission coefficients
  - Fluid density
  - Elastic properties (viscosity, Young's modulus, Bulk modulus, etc.)
  - Since sound propagation is a particle motion, we can also use sound velocity measurements to estimate volume flow rate. The perceived speed of sound is the sum of the flow rate and the wave propagation speed.
- We can also model the physics of the wave propagation in terms of other material/system properties and use numerical methods to solve the inverse problem.

Acoustic Properties of Materials

Speed of sound in different media:

- Gases: 250–400 m/s.
- Water: 1400–1550 m/s.
- Plastics: Very different, but typically in the range 2500-3000 m/s (for PMMA).
- Steel: ≈5800 m/s.
- Aluminium: ≈6420 m/s.

All depend on temperature, sound frequency, and pressure.

Acoustic Properties of Materials

Speed of sound in Biological tissue (at 37°C):

- Blood: 1560 m/s.
- Bone: 2700–4100 m/s (trabecular and cortical bone).
- Fat: 1450 m/s.
- Liver: 1560 m/s.

All depend on temperature, sound frequency, and pressure.

Acoustic Properties of Materials (cont'd...)

Frequencies for different applications:

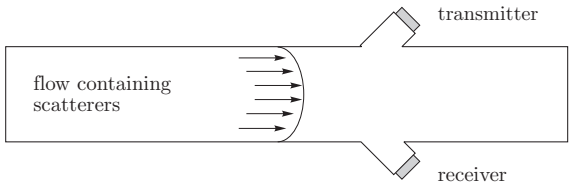
- Ultrasound in gases, typically below 1 MHz.
- Ultrasound in liquids, 500 kHz – 30 MHz, but often 3-10 MHz.
- Medical ultrasound, 3-10 MHz, in the most common systems.

Application examples

- Doppler flowmeter.
- Cross-correlation flowmeter.
- Transit-time flowmeter.
- Velocity profile measurements in multiphase flows (speckle-correlation).
- Characterization of multi-layered materials.
- Analysis of gas mixtures.

Application examples (cont'd...)

Doppler flowmeter



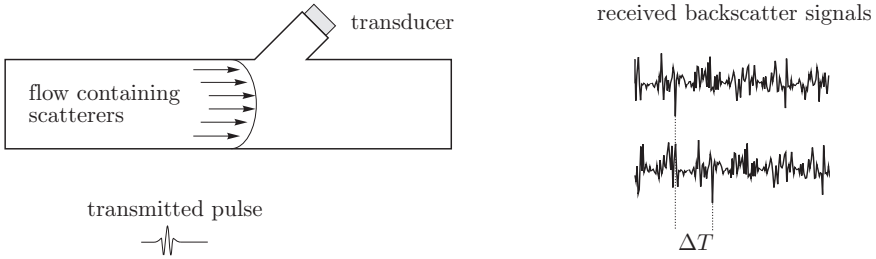
The frequency of the received signal will shift depending on the flow velocity, i.e. a Doppler effect.

$$\Delta f = f'' - f = \frac{2f}{c}\cos(\theta)v,$$

where f'' is the frequency of the received wave, f is the frequency of the transmitted wave, θ is the angle between the flow and the sensor, c is the speed of sound, and v is the average flow velocity.

Application examples (cont'd...)

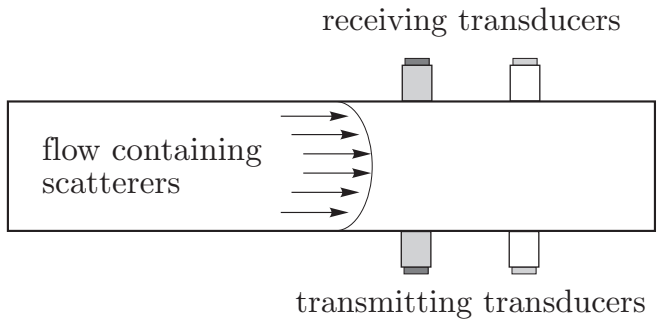
Cross-correlation flowmeter



The signal received at one time instant is cross-correlated with a signal received a short time later. The shift of the signal in time depends on the flow velocity.

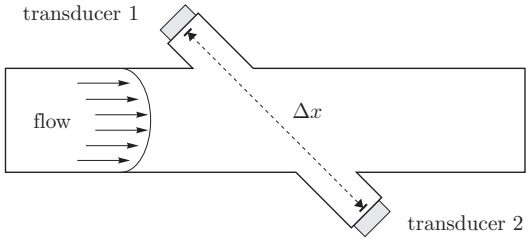
Application examples (cont'd...)

Cross-correlation flowmeter (cont'd...)



Application examples (cont'd...)

Transit-time flowmeter



The transit time of the sound differs upstream and downstream of the flow, as

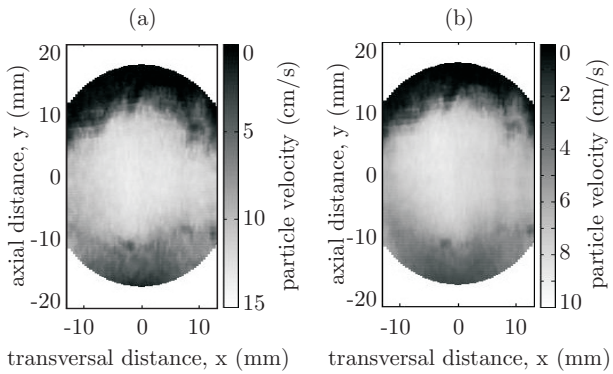
$$\Delta T = \frac{2D\cot\theta}{c^2}v,$$

where D is the distance between the sensors, θ is the angle between the flow and the sensors, c is the speed of sound, and v is the average flow velocity.

Application examples (cont'd...)

Velocity profile measurements

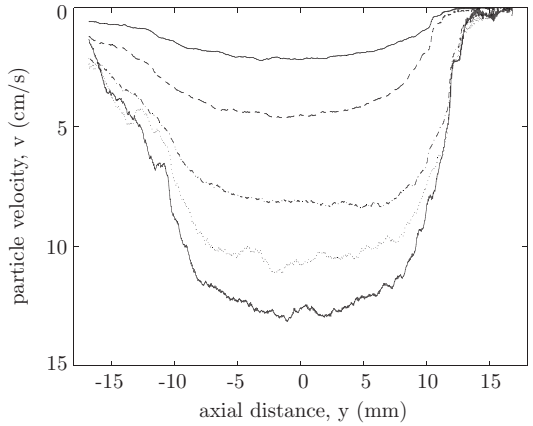
Going into more advanced instrumentation, it is possible to use the backscattered signals as a "fingerprint" (speckle pattern) of the entire flow profile. Cross-correlating two consecutive pattern, we can create a velocity profile of particles in the flow.



Application examples (cont'd...)

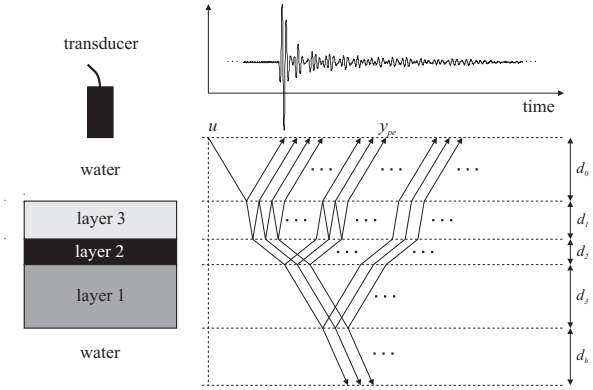
Velocity profile measurements (cont'd...)

Looking at the velocity profile at the center of the pipe, we obtain the following:



Application examples (cont'd...)

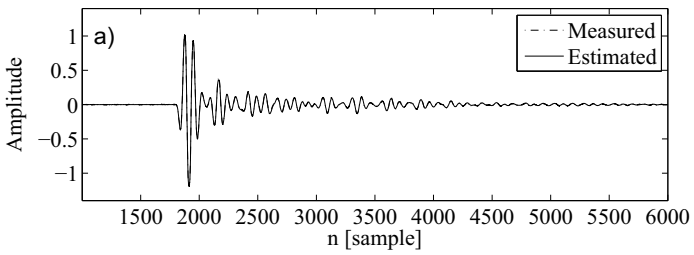
Characterization of multi-layered materials



Application examples (cont'd...)

Characterization of multi-layered materials (cont'd...)

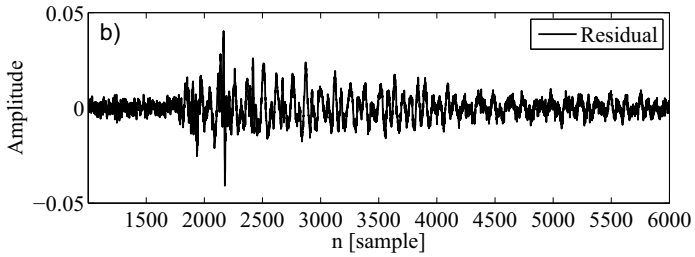
Modeling the reflections and transmissions at boundaries between the layers, and losses within the layers as a linear (dynamic) system and then using the measured pulse to estimate the model parameters, we get



Application examples (cont'd...)

Characterization of multi-layered materials (cont'd...)

A look at the model error reveals that there are some un-modeled variations, but not too much.



Analysis of energy gases

Problem

- Energy content of gases (e.g. natural gas, biogas, synthesis gas) changes with composition.
- Producers and customers need to know what the produce/buy.
- Existing techniques are expensive.
- No available technique measures flow and composition in the same instrument.

Idea

- Speed of sound and attenuation depend on molecular properties of gases, i.e. the composition.
- Gas flow can already be measured using ultrasound.

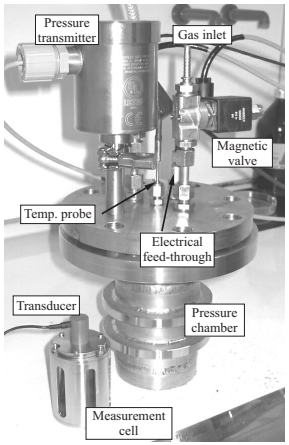
Analysis of energy gases (cont'd...)

Research approach

- Develop techniques for accurate and robust estimation of speed of sound and attenuation, based on physical knowledge of the system.
- Use some empirical regression technique to connect acoustic properties to gas composition, including also knowledge of temperature and pressure.

Analysis of energy gases (cont'd...)

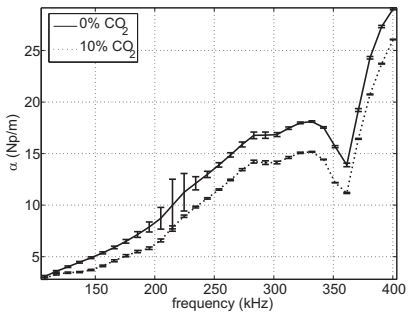
The setup

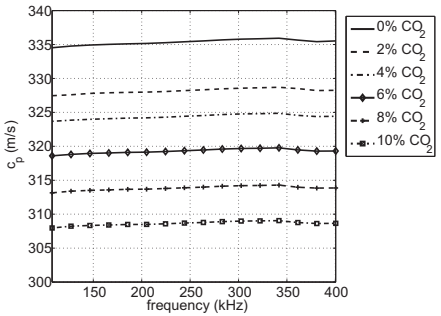


Analysis of energy gases (cont'd...)

Measurements on upgraded biogas

First, we used the measured pulse to see how speed of sound and attenuation change with gas composition.

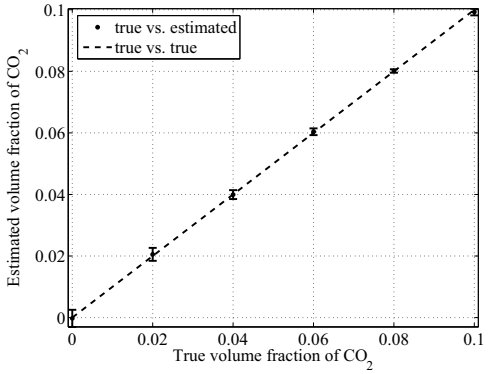




Analysis of energy gases (cont'd...)

Measurements on upgraded biogas

Then, correlate the measured quantities (acoustic properties, pressure and temperature) with gas composition.



Estimation of particle size distributions

World premiere!

Estimation of particle size distributions

Problem

- Many industrial processes use crushed materials.
- Crushing or grinding results in different particle size distributions.
- Particle sizes are important for process performance.
- How do we measure particle size distributions (for very small particles)?

Estimation of particle size distributions

Idea

- Attenuation of ultrasound depends on:
  - Ultrasound frequency (known).
  - Particle and liquid densities (known).
  - Particle sizes (unknown).
- This can be modeled from physics, given the probability density function of the particle sizes. Parameters of the probability density functions are unknown.
- Attenuation as function of frequency can be measured.

Estimation of particle size distributions

Strategy

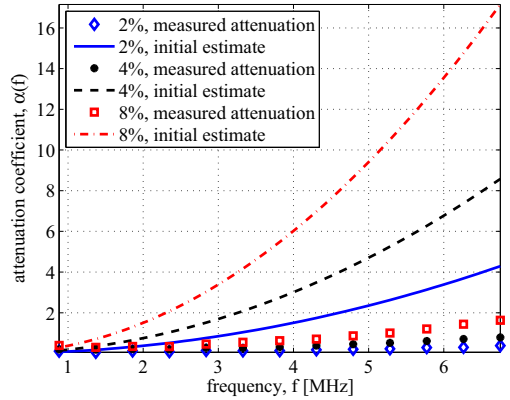
- Assume particles follow a certain distribution, described by some parameters, θ_1, θ_2, and θ_3. If the parameters were known, we could estimate the attenuation of ultrasound.
- Make an initial guess of the parameters and compute the modeled attenuation as function of frequency, let's call this $\widehat{\alpha}(f)$.
- Compare with the measured attenuation $\alpha(f)$ and form the cost function

$$J = \sum (\alpha - \widehat{\alpha})^2$$

- Use this error to update the guess of the parameters.
- Iterate!

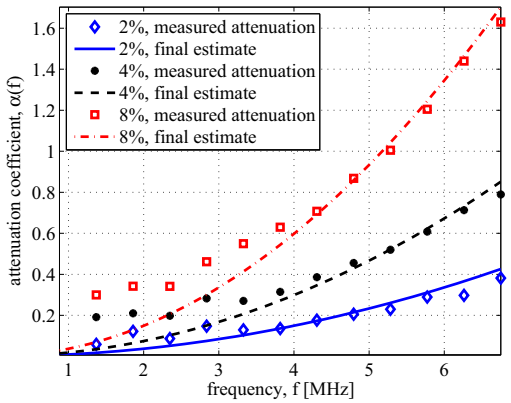
Estimation of particle size distributions

Measured and modeled ultrasound attenuation *before* algorithm was run, for three different suspensions of Dolomite particles and water:



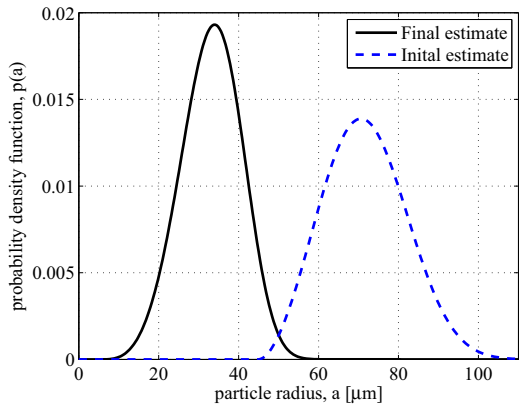
Estimation of particle size distributions

Measured and modeled ultrasound attenuation *after* the algorithm was run, for three different suspensions of Dolomite particles and water:



Estimation of particle size distributions

Estimated particle size distribution *before* (dashed line) and *after* (solid line). True particle sizes are known to be approximately 37–54 μm.



References

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- F. Hägglund, J. Martinsson, and J. E. Carlson, “Model-Based Estimation of Thin Multi-Layered Media using Ultrasonic Measurements", *IEEE Trans. on Ultrason. Ferroelectr. and Freq. Contr.*, vol. 56, no. 8, pp. 1689–1702. 2009.
- J. E. Carlson, J. Martinsson, and M. Lundberg Nordenvaad, “Measurement of Methane Content in Upgraded Biogas Using Pulse-Echo Ultrasound", *In Proc. of Int. Congr. on Ultrasonics*, Paper 1366, (Vienna, Austria), April 9–13, 2007.
- J. E. Carlson, “Estimation of Particle Size Distributions in Solid/Liquid Suspensions Based on Wide-Band Ultrasound Attenuation Measurements", accepted for presentation at *2010 IEEE Int. Ultrasonics Symposium*, (San Diego, USA), October 10–13, 2010.