Last lecture

- Capacitive sensing elements.
- Inductive sensing elements.
- Reactive Deflection bridges.
- Electromagnetic sensing elements.
- Thermoelectric sensing elements.
- Elastic sensing elements.
- Piezoelectric sensing elements.

Today's menu

- Analog-to-digital conversion (Ch. 10.1).
- Measurement of volume flow rate
  - Differential pressure flowmeters
  - Mechanical flowmeters
  - Vortex flowmeters
- Measurement of mass flow
- Measurement of "tricky flows"

Amplifiers and oscillators (Ch. 9.2 and 9.5) are covered in other courses. Read on your own as an overview.

We will skip Ch. 11 and most of Ch. 10.

A/D conversion

Analog-to-digital conversion is needed whenever we wish to process or present data using digital hardware such as a computer, microprocessor, etc.

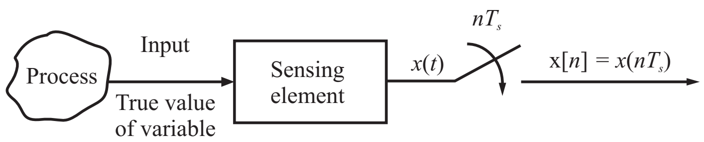
The process consists of three steps:

- Sampling
- Quantization
- Encoding

A/D conversion (cont'd...)

Sampling

The first step of the A/D conversion is to sample the continuous time signal into a discrete-time representation



- The sampling frequency $F_s = 1/T_s$ must be higher than twice the bandwidth of the signal.
- A rule-of-thumb is to sample 5–10 times the highest frequency.
- Before sampling, the signal should be filtered with a low-pass filter to ensure the bandwidth limitations are fulfilled, i.e. to avoid aliasing.

A/D conversion (cont'd...)

Sampling (cont'd...)

Examples of multi-dimensional analog-to-digital conversion

- **Digital cameras** – A two-dimensional array is used to sample an image into pixels (picture elements). The sampling distance in the plane gives the *spatial* resolution, while the number of bits per pixel is a quantization into a finite number of color values (e.g. 24 bits/pixel).
- **Antenna arrays** – Used for "beamforming" of an antenna lobe in a certain direction. The spatial resolution depends on wavelength, array pitch, and the number of elements.
- **Ultrasonic sensor arrays** – Similar to antenna arrays for radio, but made for sound waves in the MHz range. Used in all medical ultrasonic imaging systems. Could also include sampling of the time signals at each element simultaneously.

A/D conversion (cont'd...)

Medical ultrasound images

A/D conversion (cont'd...)

Quantization

The discrete-time sequence of numbers (with a continuous amplitude) is then converted into digital form by a process called "quantization".

In the quantization step, the signal amplitudes are rounded to the nearest *quantization level*.

If the range of the signal is

$$y_{\text{MAX}} - y_{\text{MIN}},$$

the spacing of the quantization interval ΔV will be

$$\Delta V = \frac{y_{\text{MAX}} - y_{\text{MIN}}}{Q - 1},$$

where Q is the number of quantization levels.

A/D conversion (cont'd...)

Quantization (cont'd...)

The finite number of levels results in a quantization error, because sample amplitudes are rounded to the closest quantization levels.

The maximum percentage quantization error is defined as:

$$e_q^{\text{MAX}} = \pm \frac{\Delta V}{2(y_{\text{MAX}} - y_{\text{MIN}})} \times 100\,\% = \pm \frac{100}{2(Q-1)}\,\%,$$

since the maximum error is equal to half the quantization step.

A/D conversion (cont'd...)

Encoding

The sampling and quantization generate a stream of quantization values, V_q, which are normally coded into a parallel digital signal.

The most common encoding is *binary*, the quantization levels are coded into a binary number.

For an 8-bit A/D converter, the number of quantization levels is $2^8 = 256$, for 10 bits, it's $2^{10} = 1024$, and so on...

Flow measurement systems

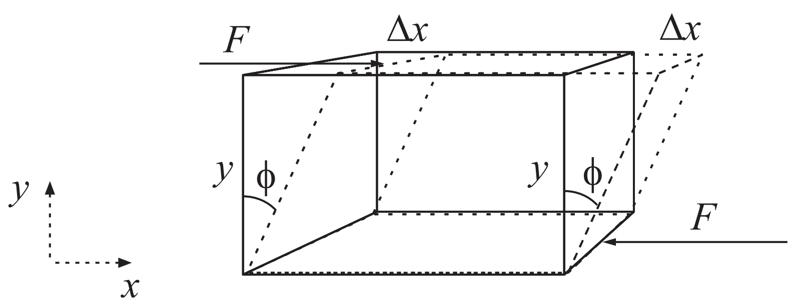
There are three states of matter:

- Solid
- Liquid
- Gas

Liquids and gases, i.e. **fluids** act in a similar way under the action of a deforming force, while solids retain their shape.

Flow measurement systems (cont'd...)

The figure shows the effect of a shear force acting on a rectangular body



In a solid, the angle ϕ will be constant over time, but in a fluid it will increase.

Flow measurement systems (cont'd...)

Liquids and gases

Although liquids and gases have common properties, they also have distinctive properties of their own:

- A liquid is difficult to compress, i.e. the density ρ is independent of pressure. It is, however dependent on temperature.
- The density of a gas is highly temperature AND pressure dependent.

Flow measurement systems (cont’d...)

Liquids and gases (cont’d...)

For an ideal gas we have:

$$\begin{aligned} PV &= mR\theta \\ P &= \rho R\theta, \end{aligned}$$

where
m = number of moles of the gas.
P = absolute pressure (Pa)
θ = absolute temperature (K)
V = volume (m^3)
ρ = density ($\mathrm{kg/m}^3$)
R = gas constant ($\mathrm{J\ kg^{-1}\ K^{-1}}$)

Flow measurement systems (cont’d...)

Liquids and gases (cont’d...)

The amount of heat required to raise the temperature of a gas depends on whether the gas is allowed to expand. It therefore has two specific heats:

- The specific heat at constant pressure, C_P.
- The specific heat at constant volume, C_V.

If expansion or contraction is **adiabatic**, i.e. no heat enters or leaves the system, the relationship between pressure and volume becomes

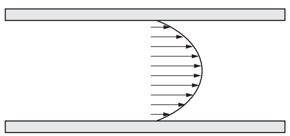
$$PV^\gamma = \frac{P}{\rho^\gamma} = \text{constant},$$

where $\gamma = C_P/C_V$.

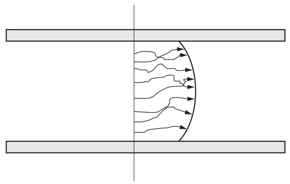
Flow measurement systems (cont’d...)

Laminar or turbulent flow

Two distinct types of flow can exist, laminar and turbulent



Laminar flow



Turbulent flow

For laminar flow, the fluid velocity at each point is in the flow direction.

For turbulent flow, the fluid velocity at each point is random, but the average flow is in one direction.

Flow measurement systems (cont’d...)

Laminar or turbulent flow (cont’d...)

The **Reynolds number** tells us whether a flow is laminar or turbulent, defined as

$$Re = \frac{vl\rho}{\eta},$$

where l is the diameter of the pipe, v is the flow velocity, ρ is the density, and η is the dynamic viscosity of the fluid.

Flow measurement systems (cont'd...)

Laminar or turbulent flow (cont'd...)

The following approximations can serve as a guide:

$$
\begin{aligned}
Re < 2 \times 10^3 \quad &- \quad \text{laminar flow} \\
2 \times 10^3 < Re < 10^4 \quad &- \quad \text{transition region} \\
Re > 10^4 \quad &- \quad \text{turbulent flow}
\end{aligned}
$$

Flow measurement systems (cont'd...)

Volume flow rate

The volume flow rate through a cross sectional area is defined as

$$Q = \int_A v(x, y) dA.$$

For the special case of a circular pipe with radius R, this is

$$Q = 2\pi \int_0^R v(r) r \, dr.$$

The mean velocity is given by

$$\overline{v} = \frac{Q}{A}.$$

Flow measurement systems (cont'd...)

Mass flow rate

The mass flow rate is given by the volume flow rate and the density, as

$$\dot{M} = \rho Q.$$

Most flow meters measure the volume flow rate, but there are those that directly measure mass flow (e.g. the coriolis flow meter).

Flow measurement systems (cont'd...)

Physical principles of flow measurement

There are a couple of fundamental properties that can be explored when designing a flow measurement system:

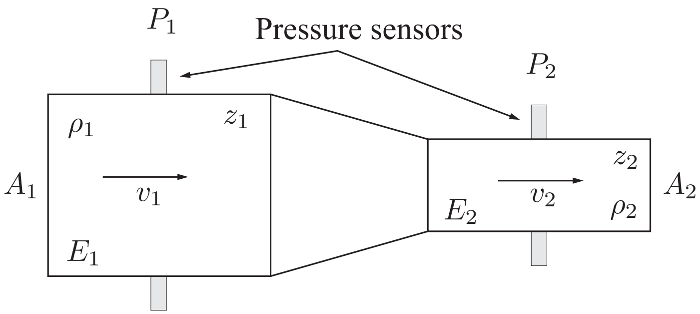
- **Continuity:** Under steady flow conditions, the amount of mass entering a tube is the same as the amount that leaves the tube. This means flow rate in equals the flow rate out!
- **Conservation of energy:** This means the “work in" must equal “work out", accounting for heat losses due to friction or molecular phenomena.

Read 12.1.6 for details.

Measurement of volume flow rate

Differential pressure flow meters

These are the most common industrial flowmeters for clean liquids and gases.



Venturi tube

Measurement of volume flow rate (cont'd...)

Differential pressure flow meters (cont'd...)

Cross section average velocity	v_1	v_2	m/s
Pressure	P_1	P_2	N/m^2
Fluid cross section area	A_1	A_2	m^2
Fluid density	ρ_1	ρ_2	kg/m^3
Total energy/mass	E_1	E_2	J/kg
Elevation above datum	z_1	z_2	m

Measurement of volume flow rate (cont'd...)

Differential pressure flow meters (cont'd...)

Assumptions when deriving the equations:

- Frictionless flow
- No heat losses
- Conservation of energy (pressure + kinetic + potential), i.e.

$$E_1 = \frac{P_1}{\rho_1} + \frac{1}{2}v_1^2 + gz_1 = E_2 = \frac{P_2}{\rho_2} + \frac{1}{2}v_2^2 + gz_2$$

- Incompressible fluid, i.e. $\rho_1 = \rho_2 = \rho$.
- Conservation of volume flow rate, i.e. $Q_1 = A_1 v_1 = Q_2 = A_2 v_2$.

Measurement of volume flow rate (cont'd...)

Differential pressure flow meters (cont'd...)

- Horizontal pipe, i.e. $z_1 = z_2$. This means that the equation simplifies to

$$\begin{aligned} \frac{P_1}{\rho_1} + \frac{1}{2}v_1^2 &= \frac{P_2}{\rho_2} + \frac{1}{2}v_2^2 \\ \frac{v_2^2 - v_1^2}{2} &= \frac{P_1 - P_2}{\rho} \end{aligned}$$

Measurement of volume flow rate (cont'd...)

Differential pressure flow meters (cont'd...)

We now have all the equations we need to solve for the theoretical volume flow rate, Q, i.e.

$$
\begin{aligned}
Q &= A_1 v_1 \\
A_1 v_1 &= A_2 v_2 \\
\frac{v_2^2 - v_1^2}{2} &= \frac{P_1 - P_2}{\rho},
\end{aligned}
$$

which gives (after some calculations...)

$$Q = \frac{A_2}{\sqrt{1 - \left(\frac{A_2}{A_1}\right)^2}} \sqrt{\frac{2(P_1 - P_2)}{\rho}}$$

Measurement of volume flow rate (cont'd...)

Differential pressure flow meters (cont'd...)

Some assumptions are not fulfilled in practice:

- Frictionless flow is not obeyed, but for well-established turbulent flow ($Re > 10^4$) the losses are small.
- The cross section area of the flow is not the same as the cross section area of the pipe. This depends on the velocity and the pipe diameter ratio.
- For gases, the fluid is compressible.

To account for this, correction factors are introduced. These are then determined in calibration experiments. See the book for the details on how the equation is simplified.

Measurement of volume flow rate (cont'd...)

Differential pressure flow meters (cont'd...)

General characteristics of D/P flowmeters:

- No moving parts; robust, easy to maintain; widely established and accepted.
- Permanent pressure loss due to frictional effects. This could mean a significant cost in increased pumping energy.
- Non-linear devices; The useful range is limited to between 25% and 100 % of maximum flow.
- Can only be used for clean fluids.
- Limited accuracy ($\approx$ 1.5 %).

Measurement of volume flow rate (cont'd...)

Mechanical flowmeters

A mechanical machine is placed in the flow, which moves with a cycle f proportional to the flow rate, i.e.

$$f = KQ.$$

Mechanical flowmeters measure the volume V that has been delivered

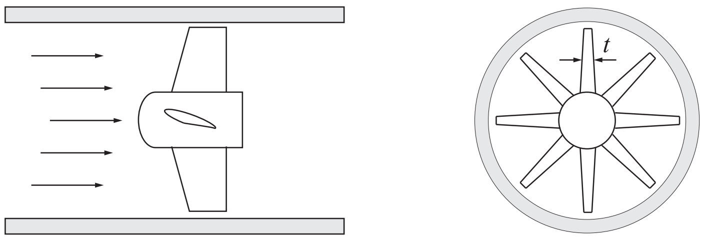
per time period T, i.e. by counting the number of cycles over the time T.

$$N = \int_0^T f\,dt = K \int_0^T Q\,dt = KV.$$

Measurement of volume flow rate (cont'd...)

Mechanical flowmeters (cont'd...)

Turbine flowmeters



Measurement of volume flow rate (cont'd...)

Mechanical flowmeters (cont'd...)

Turbine flowmeters

- The blades of the turbine are usually made of a ferromagnetic material.
- The rotation can be picked up by an electromagnetic sensing element, which output voltage will be a sinusoidal with a frequency proportional to the volume flow rate.

Measurement of volume flow rate (cont'd...)

Mechanical flowmeters (cont'd...)

Properties of turbine flowmeters

- Moving mechanical parts; ageing and wear of bearings leading to high maintenance costs.
- Poor reliability.
- Flow rate found by calibration.

Measurement of volume flow rate (cont'd...)

Vortex flow meters

General principle

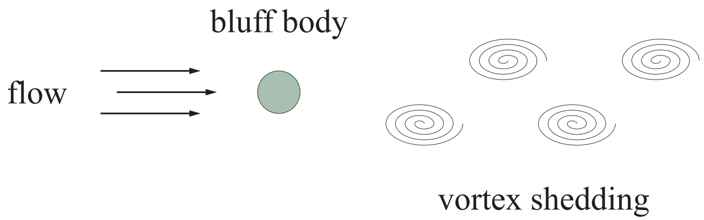
- Based on a natural phenomenon called **vortex shedding**.
- When a fluid flows over a body, vortices will form in the flow due to boundary conditions.
- The vortex frequency is proportional to the flow rate, as

$$f = S\frac{v}{d},$$

  where d is the diameter of the bluff body and S is the Strouhal number (constant for a wide range of flow).
- The vortices give rise to local changes in pressure and velocity, which enables "counting" or detection of the vortices.

Measurement of volume flow rate (cont'd...)

Vortex flow meters (cont'd...)



Measurement of volume flow rate (cont'd...)

Vortex flow meters (cont'd...)

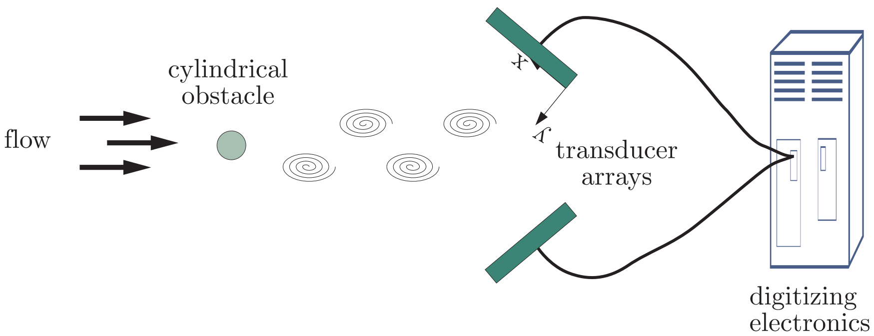
Detection of vortices:

- **Piezoelectric** – Flexible diaphragms (membranes) in the bluff body react to the local variations in pressure.
- **Thermal** – For small flows (see Ch. 14.2 and 14.3 for details).
- **Ultrasonic** – The ultrasound signal is modulated in both amplitude and frequency because of local variations in pressure and velocity.

Measurement of volume flow rate (cont'd...)

Vortex flow meters (cont'd...)

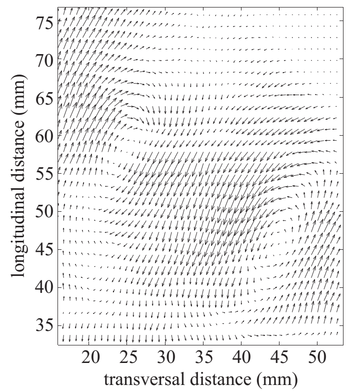
Ultrasonic imaging of vortices



Measurement of volume flow rate (cont'd...)

Vortex flow meters (cont'd...)

Ultrasonic imaging of vortices



J. Carlson, R.-K. Ing, J. Bércoff, and M. Tanter, "Ultrasonic vortex imaging using two-dimensional speckle correlation", IEEE Int. Ultrason. Symp. 2001.

Measurement of mass flow rate

Inferential methods

Here, the mass flow is computed from volume flow and density, i.e.

$$\dot{M} = \rho Q$$

and

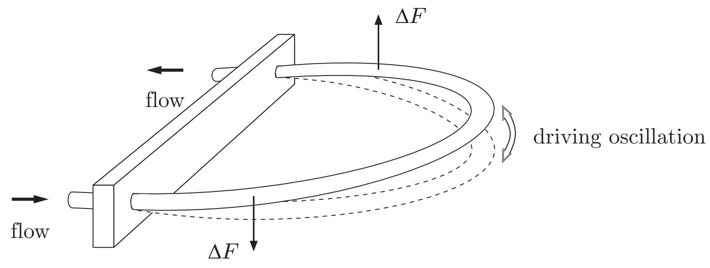
$$M = \rho V.$$

Examples of ultrasonic mass flow metering will be given next lecture.

Measurement of mass flow rate (cont'd...)

Direct methods - the coriolis effect

This means measuring the mass flow directly. The most common direct mass flow meter in use today is the coriolis meter.



Measurement of mass flow rate (cont'd...)

Direct methods - the coriolis effect (cont'd...)

General principle:

- The flow of a certain mass passes through a U-shaped tube section that rotates with a certain angular frequency.
- The mass experiences a force proportional to the flow velocity, the mass, and the rotation frequency.
- The force variations can be measured using for example strain gauges.
- Read the details on your own.

Measurement of “tricky flows"

Examples

- The flow is slow (laminar) or transitional $Re < 10^4$. Differential pressure meters work poorly.
- The fluids are highly corrosive or toxic. Mechanical meters like turbine meters can not be used.
- Multiphase flows. The flow contains liquids, solids and gases. Physical modeling leading to the equations become extremely difficult.
- No obstruction can be tolerated. For example, measuring blood flow, or in situations where no pressure drops can be tolerated.

Read the remaining sections as an overview.

Summary

- Analog-to-digital conversion (Ch. 10.1).
- Introduction to flow measurement systems (Ch. 12.1).
- Measurement of volume flow rate
  - Differential pressure flowmeters
  - Mechanical flowmeters
  - Vortex flowmeters
- Measurement of mass flow
- Measurement of “tricky flows"