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).
- Introduction to flow measurement systems (Ch. 12.1).

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 all 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...)

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 quantization interval \(\Delta V\) will be

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

where \(Q\) is the number of quantization levels.

Medical ultrasound images

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.

The force results in a shear stress $\tau$, given by $F/A$, where $A$ is the base area of the block.

The resulting strain is quantified by the angle $\phi$, given by

$$\tau = \eta \frac{dv}{dy},$$

where $\eta$ is the dynamic viscosity of the fluid, and $v = dx/dt$ is the velocity gradient.

Flow measurement systems (cont’d…)

In a solid, the angle $\phi$ 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 $\rho$ is independent of pressure. It is, however dependent on temperature.
- The density of a gas is highly temperature AND pressure dependent.

For an ideal gas we have:

$$PV = mR\theta$$

$$P = \rho R\theta,$$

where $m = \text{number of moles of the gas}$.

$P = \text{absolute pressure (Pa)}$

$\theta = \text{absolute temperature (K)}$

$V = \text{volume (m}^3\text{)}$

$\rho = \text{density (kg/m}^3\text{)}$

$R = \text{gas constant (J kg}^{-1}\text{K}^{-1}\text{)}$

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

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, \( \rho \) is the density, and \( \eta \) is the dynamic viscosity of the fluid.

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

\[ v = \frac{Q}{A}. \]

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 measures 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.

Summary

- Analog-to-digital conversion (Ch. 10.1).
- Introduction to flow measurement systems (Ch. 12.1).

Next lecture

- Actual flow measurement, i.e. the rest of Ch. 12.

Recommended exercises

- None... yet 😊
Questions?