ELEC 207
Instrumentation and Control

7 – Displacement Transducers (1)

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Displacement measurement

Displacement, position and level

Displacement is defined as the movement of an object from one position to another. It can be:

- **Translational** (movement along a straight line);
- **Rotational** (angular movement).

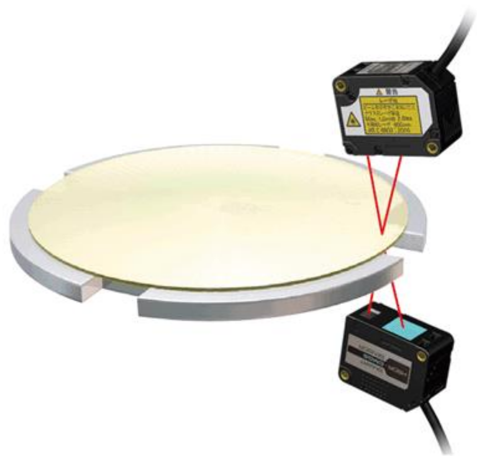
Displacement is measured by measuring a (new) position with respect to a reference (old) position:

- A displacement measurement is equivalent to a **position** or **level** measurement;
- It has a wide range of applications (robotics, process feedback control, performance evaluation, industrial automation, etc.).

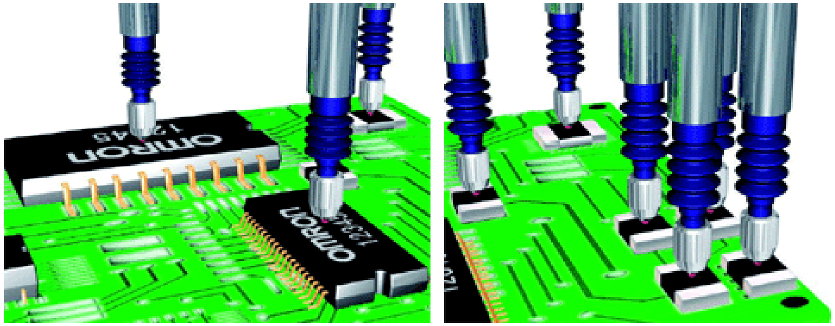
Displacement measurement

Application examples in industrial automation

- Semiconductor industry:



Wafer thickness measurement



Height measurement of electronic components

- Beverage industry:

Detection of fallen parts

Displacement measurement

Types of transducers (1)

Displacement and level transducers are based on different physical principles and technologies:

- **Resistive**:
  - Typically based on potentiometers;
  - A relatively simple and low-cost technology used in many applications.

- **Capacitive**:
  - Used for high-resolution **non-contact** measurement of conductive targets;
  - Used also to measure the thickness or density of non-conductive materials.

Displacement measurement
Types of transducers (2)

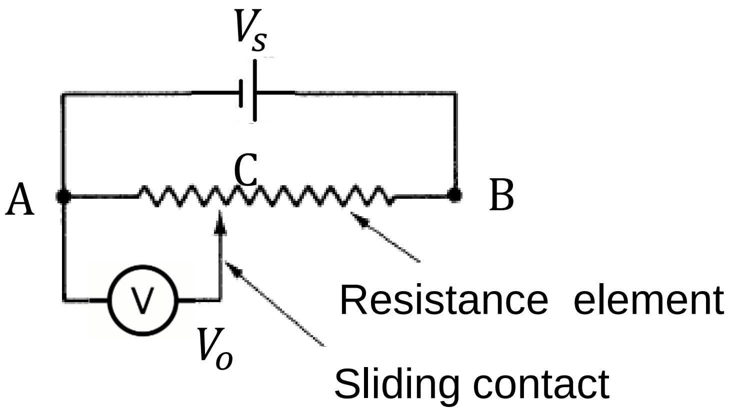
- **Inductive**:
  - ➢ Reliable under harsh conditions, high signal quality and good temperature stability;
  - ➢ Allow also non-contact measurements.

- **Optical**:
  - ➢ Used for non-contact measurements;
  - ➢ Typically employed to detect the position or rotational speed of a rotating shaft;
  - ➢ Based on at least three essential components: a light source, a light detector and a light guidance device (e.g. lenses, mirrors, optical fibres, etc.).

Resistive potentiometer

Principle of operation

A potentiometer consists of a resistor and a sliding contact:



- It acts as a resistive **voltage divider**:

$$V_o = V_s \frac{R_{AC}}{R_{AB}}$$

- The body whose motion is being measured is connected to the sliding contact:
  - There is a **linear relationship** between the distance AC (position of the body) and the output voltage:

$$V_o = V_s \frac{AC}{AB}$$

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Resistive potentiometer

Drawbacks and limitations

This type of transducer is simple and low-cost, but not very accurate:

- If the resistance value is **high**, the resistance of the instrument measuring the output voltage (e.g., a voltmeter) can affect the output value (**loading effect**);
- If the resistance value is **low**, the output can be affected by the additional resistance of connecting wires (**parasitic resistance**);
- Moreover, in case of wire-wound potentiometers, the **resolution** is limited by the step increment (one turn of the wire):
  - ➢ Carbon-film or plastic-film potentiometers can be used to overcome this limitation.

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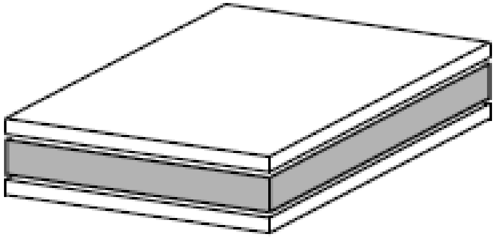
Capacitive transducer
Principle of operation

The capacitance of a capacitor with parallel conducting plates is:



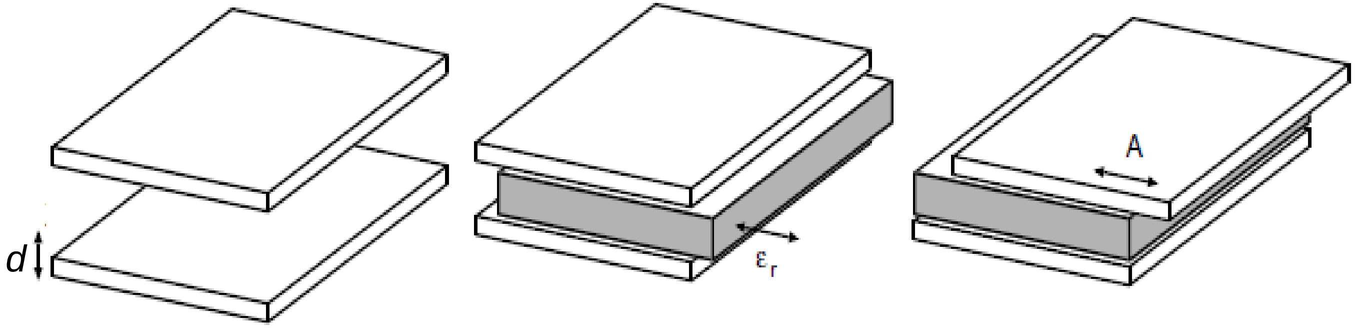
$$C = \varepsilon_0 \varepsilon_r \frac{A}{d}$$

A: area of the plates

d: distance between them

ε_r: dielectric constant of the insulator

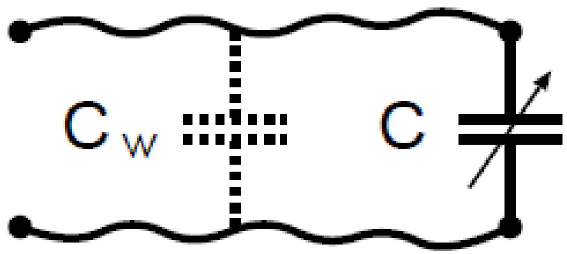
- Displacement can be sensed by varying any of the three variables: ε_r, A, d:
  - Only variations of ε_r and A produce a **linear response**.



Capacitive transducer

Drawbacks and limitations

The capacitance measurement is affected by the **wiring capacitance**, which is in parallel to the capacitor and therefore is added to the total measured capacitance:



- A small change in the capacitance value can be affected by a large error;
- Using the **plate separation** *d* to measure the displacement would result in a higher sensitivity (and better accuracy), but the response would be **non-linear**.

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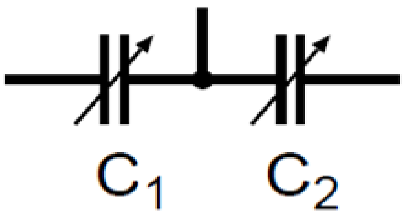
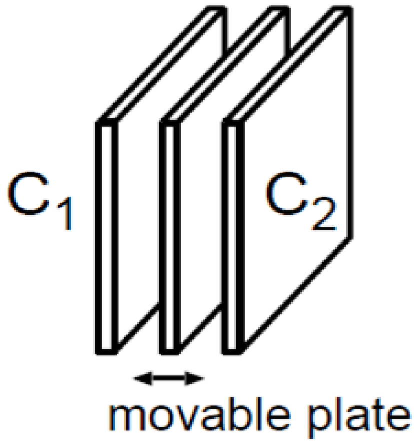
Differential capacitance transducer

Change in plate separation

The transducer response can be made linear by using a **differential capacitance transducer**:

- One movable plate is placed between two fixed plates, thus producing two variable capacitors:





- The capacitance change corresponding to a displacement can be measured by a **capacitance bridge**.

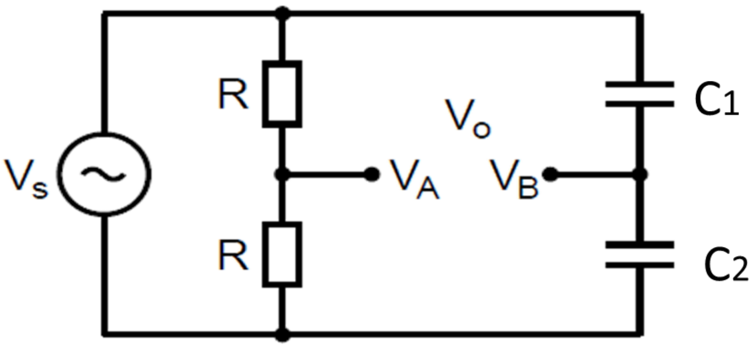
Differential capacitance transducer

Capacitance bridge (1)

The change in capacitance can be measured by an **AC bridge**:

$$V_o = V_B - V_A = V_s \frac{\frac{1}{j\omega C_2}}{\frac{1}{j\omega C_1} + \frac{1}{j\omega C_2}} - \frac{V_s}{2} =$$

$$= V_s \left(\frac{C_1}{C_1 + C_2} - \frac{1}{2} \right)$$



- When the movable electrode is in the central position, the bridge is **balanced**:

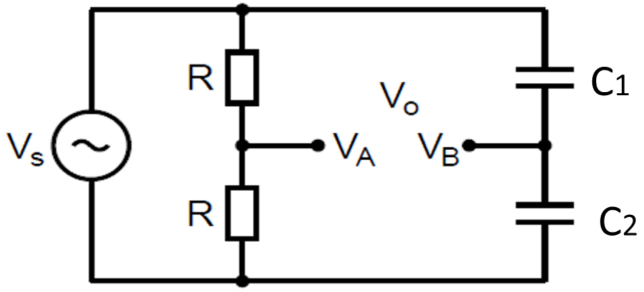
$$C_1 = C_2 \quad \Longrightarrow \quad V_o = 0$$

Differential capacitance transducer

Capacitance bridge (2)

- When the movable electrode is shifted by Δx (e.g. to the right), an unbalance appears:

$$C_1 = \varepsilon_0 \varepsilon_r \frac{A}{d + \Delta x} \quad , \qquad C_2 = \varepsilon_0 \varepsilon_r \frac{A}{d - \Delta x}$$



- In this case the **output voltage** of the bridge is:

$$V_o = V_s \left(\frac{C_1}{C_1 + C_2} - \frac{1}{2} \right) = V_s \left(\frac{\frac{1}{d + \Delta x}}{\frac{1}{d + \Delta x} + \frac{1}{d - \Delta x}} - \frac{1}{2} \right) =$$

$$= V_s \left(\frac{1}{\frac{d - \Delta x + d + \Delta x}{d - \Delta x}} - \frac{1}{2} \right) = V_s \left(\frac{d - \Delta x}{2d} - \frac{1}{2} \right) = -V_s \frac{\Delta x}{2d}$$

Differential capacitance transducer
Transfer function

The transfer function of this transducer is therefore:

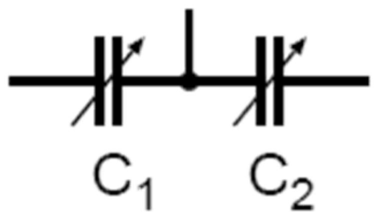
$$V_o = -V_s \frac{\Delta x}{2d}$$

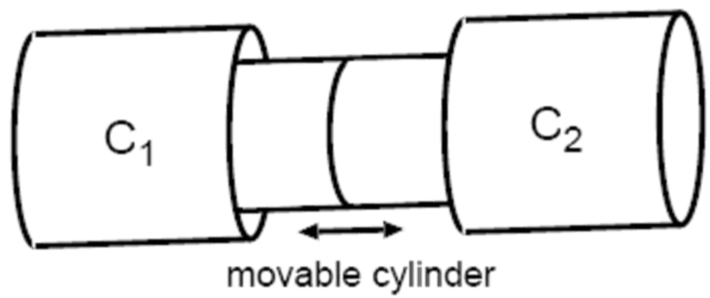
- The bridge is an AC circuit, so V_s and V_o are **phasors**:
  - ➢ The **magnitude** of V_o is proportional to the magnitude of the displacement;
  - ➢ The **phase** of V_o provides the direction of the displacement.
- Therefore both amplitude and phase must be measured.

Differential capacitance transducer

Change in overlapping area

An alternative solution is to change the **overlapping area** of plates in a differential capacitance transducer:





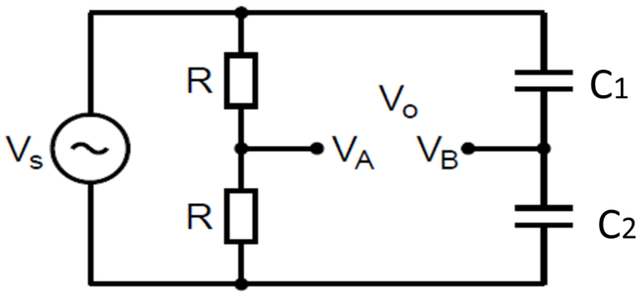
- The movement of the movable cylinder produces an opposite change in the overlapping electrode areas in the two capacitors:

$$C_1 = \varepsilon_0 \varepsilon_r \frac{A - \Delta A}{d} \quad , \qquad C_2 = \varepsilon_0 \varepsilon_r \frac{A + \Delta A}{d}$$

Differential capacitance transducer

Capacitance bridge

A capacitance bridge can be used again to convert this change in capacitance into a voltage:



- The **output voltage** of the bridge is now:

$$V_o = V_s\left(\frac{C_1}{C_1 + C_2} - \frac{1}{2}\right) = V_s\left(\frac{A - \Delta A}{A - \Delta A + A + \Delta A} - \frac{1}{2}\right) =$$

$$= V_s\left(\frac{A - \Delta A}{2A} - \frac{1}{2}\right) = -V_s\frac{\Delta A}{2A}$$

- Since $\Delta A = L\Delta x$ (being L the circumference of the cylinder), the output voltage is proportional to the displacement Δx as well.

References

Textbook: Principles of Measurement Systems, 4th ed.

For further explanation about the points covered in this lecture, please refer to the following chapters and sections in the **Bentley** textbook:

- Chapter 8, Sec. 8.1.1: **Potentiometers for linear and angular displacement measurement**;
- Chapter 8, Sec. 8.2: **Capacitive sensing elements**;
- Chapter 9, Sec. 9.1.3: **Design of reactive deflection bridges**.

NOTE: Topics not covered in the lecture are not required for the exam.

References

Textbook: Measurement and Instrumentation, 2nd ed.

For further explanation about the points covered in this lecture, please refer to the following chapters and sections in the **Morris-Langari** textbook:

- Chapter 19, Sec. 19.2.1: **Resistive potentiometer**;
- Chapter 19, Sec. 19.2.3: **Variable capacitance transducers**;
- Chapter 7, Sec. 7.2.4: **AC bridges**.

NOTE: Topics not covered in the lecture are not required for the exam.