Aalto-yliopisto
Sähkötekniikan korkeakoulu

Pressure measurements

ELEC-E5710 Sensors and Measurement Methods

Pressure

- Compressed gas or liquid aims to expand, this is called pressure.
- Defined as a ratio of force and surface area

$$p = \frac{F}{A}$$

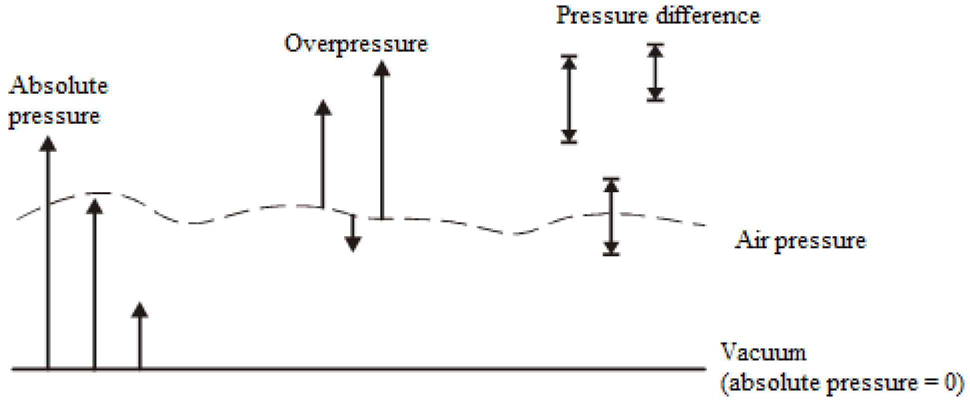
- SI unit for pressure is Pascal,
  - $Pa = N/m^2 = kg/m/s^2$
- After temperature, pressure is the second most measured process quantity.

Units of pressure

	Pa	bar	psi	at	atm	Torr	mmHg	inHg	cmH_2O
1 Pa	1	10^{-5}	$1.45 \cdot 10^{-4}$	$1.02 \cdot 10^{-5}$	$9.87 \cdot 10^{-6}$	$7.5 \cdot 10^{-3}$	$7.5 \cdot 10^{-3}$	$2.96 \cdot 10^{-4}$	0.0102
1 bar	10^{5}	1	14.5	1.02	0.987	750	750	29.6	1020
1 psi	6890	689	1	0.070	0.068	51.7	51.7	2.04	70.3
1 at	$9.81 \cdot 10^{4}$	0.981	14.2	1	0.968	736	736	29	1000
1 atm	101325	1.01	14.7	1.03	1	760	760	30	1030
1 Torr	133	$1.33 \cdot 10^{-3}$	0.0193	$1.36 \cdot 10^{-3}$	$1.32 \cdot 10^{-3}$	1	~1	0.0395	1.36
1 mmHg	133	$1.33 \cdot 10^{-3}$	0.0193	$1.36 \cdot 10^{-3}$	$1.32 \cdot 10^{-3}$	~1	1	0.0395	1.36
1 inHg	3380	338	0.49	0.0344	0.033	25.3	25.3	1	34.4
1 cmH_2O	98.1	$9.81 \cdot 10^{-4}$	0.0142	0.001	$9.68 \cdot 10^{-4}$	0.736	0.736	0.029	1

Types of pressure

- Absolute pressure
  - Compared to vacuum, so pressure is always greater than zero
  - Meters for small absolute pressure are called vacuum gauges
- Current air pressure
  - Depends on circumstances, altitude etc.
  - Gauges are called barometers, absolute measurement
- Overpressure and underpressure
  - Reference pressure is the current air pressure
- Pressure difference measurement
  - Reference value is something else than vacuum or current air pressure



Static and dynamic pressure

- Static pressure: static pressure is measured when the fluid is at rest

$$p$$

- Dynamic pressure: caused by directional kinetic energy of matter

$$\frac{1}{2}\rho v^2$$

- Total pressure = static pressure + dynamic pressure

Hydrostatic pressure

- Pressure caused by the gravitational force of the liquid or gas:

$$p = \rho g \Delta h$$

ρ = fluid density ; g = gravitational acceleration; h = depth of fluid

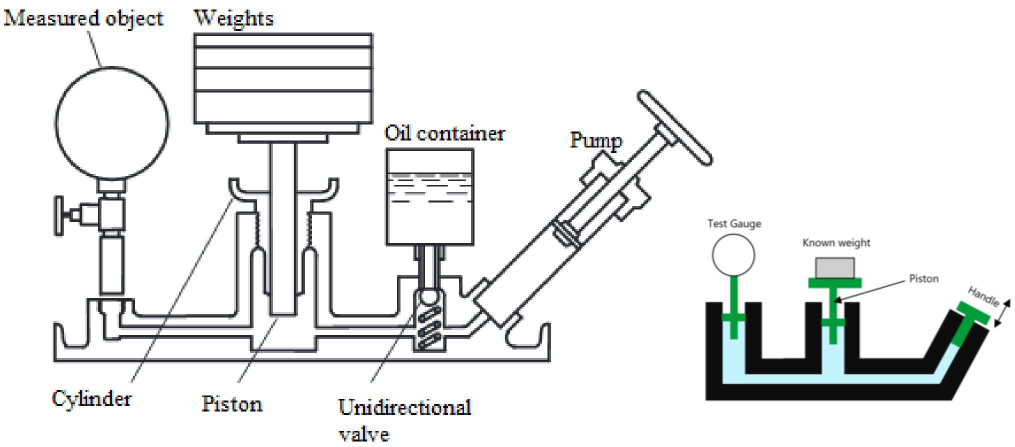
Measuring instruments

- Calibrating instruments are based on the definition of pressure
  - Dead weight testers
  - Manometers

- Field measuring instruments
  - Transitional and force sensors
  - For special applications e.g. thermic and ionization measuring instruments

Dead weight tester

- Typical calibrating device for meters
- Transforms the mass of weights to liquid or gas pressure with the help of a cylinder and a piston
- High accuracy is obtained by dimensional measurements (the diameter of the piston)

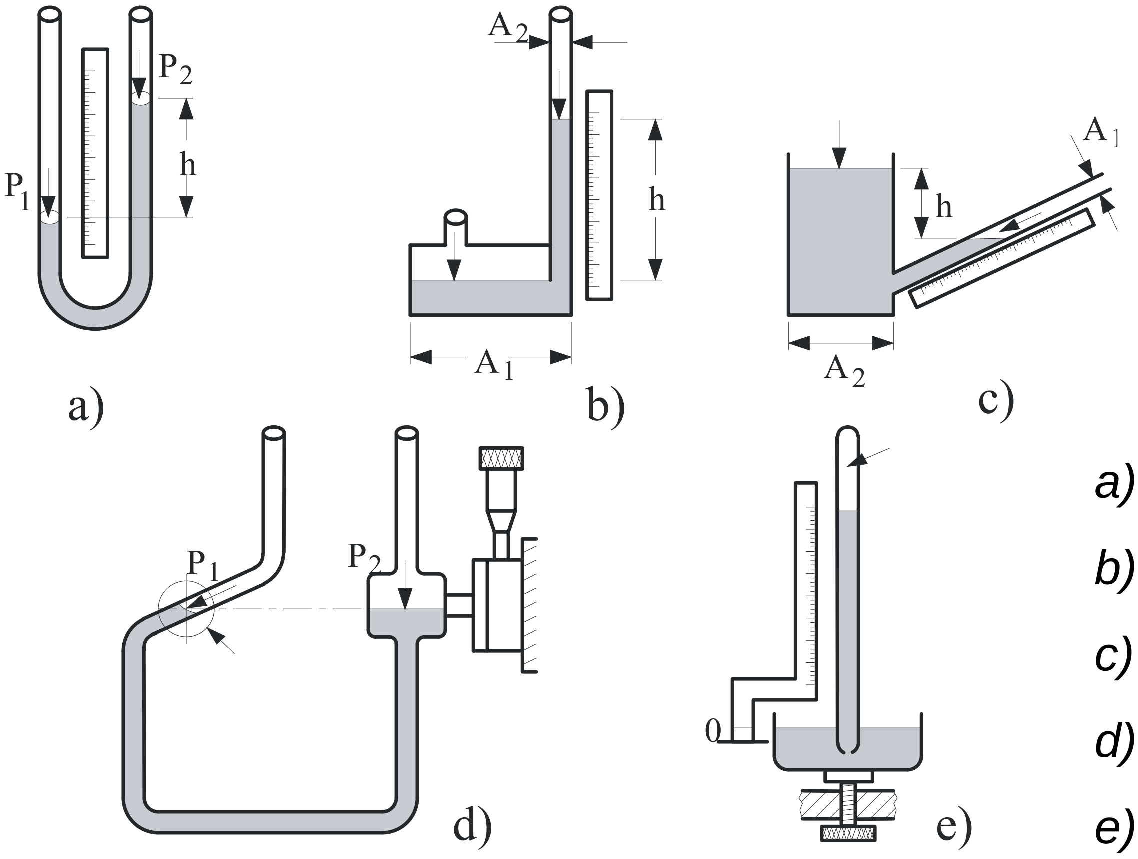


Schematic diagram: Dead Weight Tester

Dead weight tester

- Air or nitrogen as a medium when the pressure is low (1kPa – 5 MPa) and oil or water with higher pressure (5 MPa – 2,5 GPa)
- Problems
  - Small pressure: friction
  - High pressure: elastic deformation of the cylinder-piston combination
- Important during calibration
  - Determination of the effective area of the cylinder piston
  - Determination of the mass of the weights

Manometer



a) *U-tube manometer,*

b) *Well type manometer,*

c) *Inclined tube manometer,*

d) *Micro manometer*

e) *Barometer*

Manometer

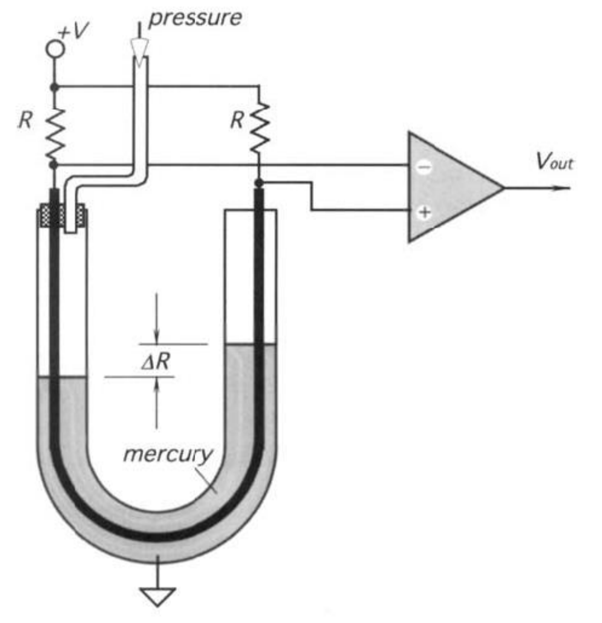
- Filled with water, mercury or e.g. butyl alcohol
- Pressure difference $p_1 - p_2$ can be calculated from the altitude difference of the columns

$$p_1 - p_2 = \rho g h, \; A_2 = A_1$$

$$p_1 - p_2 = \rho g h \left(1 + \frac{A_2}{A_1}\right), \; A_2 \neq A_1$$

Manometer (example)

- U-shaped resistive wire in mercury which short circuit the wire
- Measuring with a bridge connection
  - Equilibrium when the pressure difference of the tube is zero
  - When the other side is exposed to pressure, the bridge connection is not in equilibrium and there is an output signal
- When the pressure increases on the left side, the resistance also increases. On the other side, the resistance decreases
- The output voltage is proportional to the resistance difference

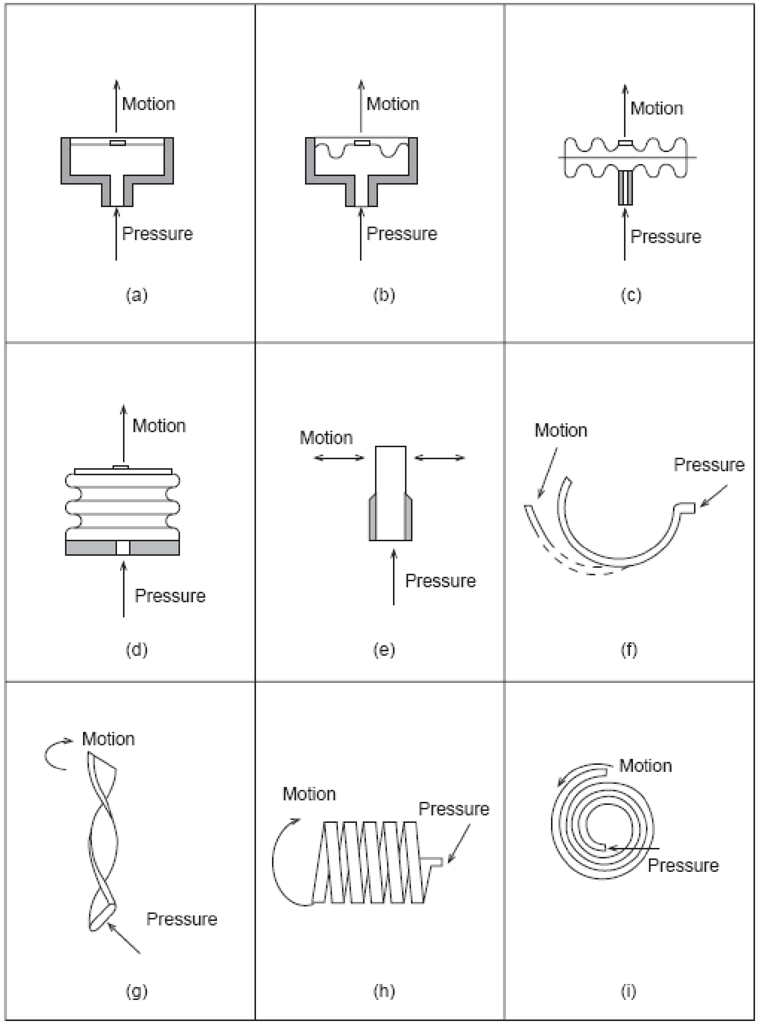


Manometer (example)

- Pros:
  - Simple and reliable instrument to measure gas pressure
  - Inexpensive
- Cons:
  - Low time constant
  - Sensitivity to vibrations
  - Large
  - Mercury contaminates the gas

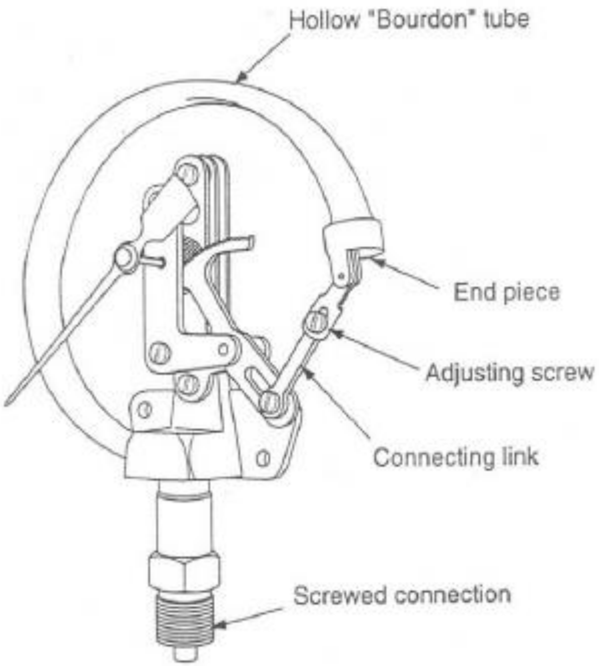
Mechanical pressure sensors (no fluid)
- transition pressure sensors

(a) Flat film
(b) Waved film
(c) Capsule
(d) Bellows
(e) Straight tube
(f) C-shaped bourdon tube
(g) Bent bourdon tube
(h) Twisted bourdon tube
(i) Spiral bourdon tube



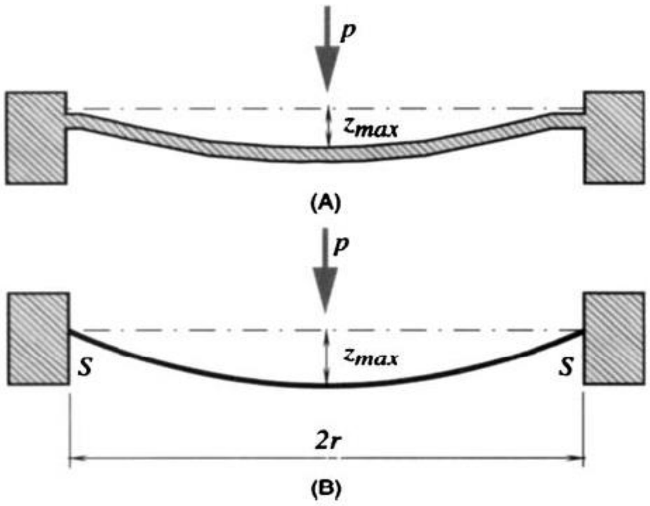
Bourdon tube

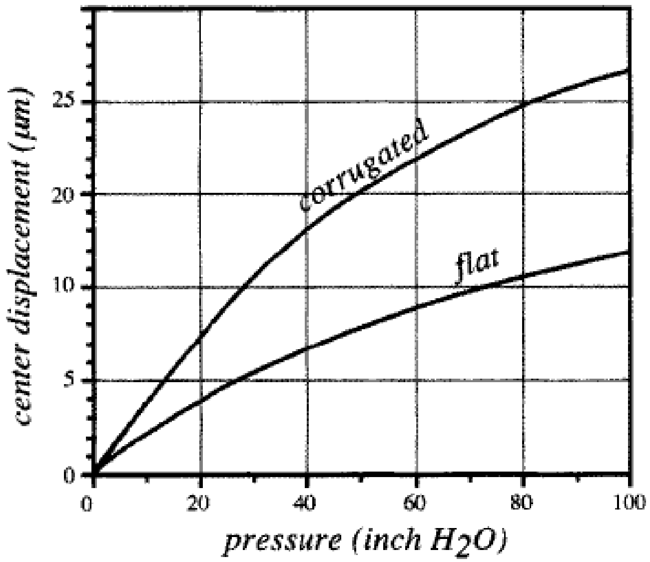
- Flat tube made of brass or steel
- Functioning based on springback factor
- Inexpensive, reasonable overall accuracy in pressure gauges
- Absolute pressure up to 6 MPa and overpressure up to 700 MPa



Flexible film

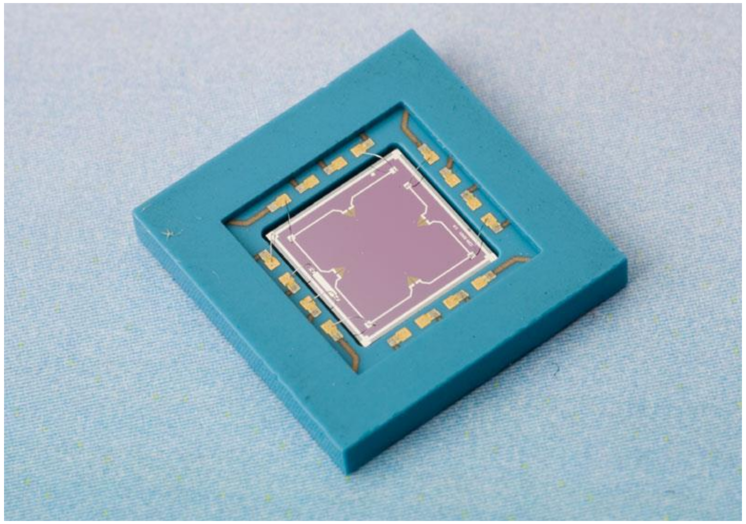
- Sensitivity can be enhanced by corrugating the film
  - Releases tension in the film
  - Enhanced sensitivity and linearity





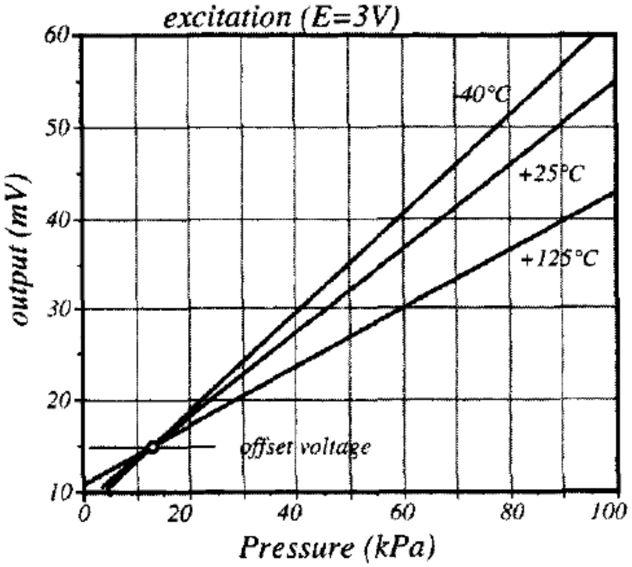
Piezoresistive pressure sensor

- The most common type,
  - To all applications
- Typically a semiconductor stretch slip attached to a flexible film
- Measurement with a Wheatstone bridge



Temperature dependency of a piezo pressure sensor

- The temperature coefficient of a piezo sensor's sensitivity is negative and rather big
- Temperature compensation is required
  - Often with bridge connections

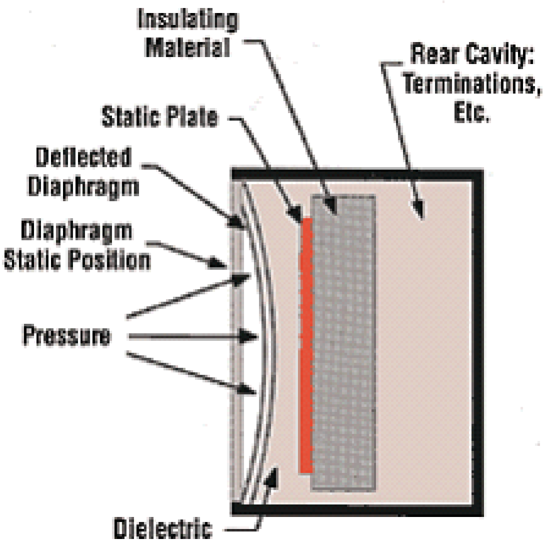


Strain gauge pressure sensor

- Electrical resistance of a strain gauge changes when material deforms.
- When a material comes longer and narrower, its resistance changes.

Capacitive pressure sensor

- Other electrode (e.g. silicon) functions a pressure-displacement transformer while the other one is fixed
- As pressure increases the distance between the electrodes decreases
  - Capacitance increases

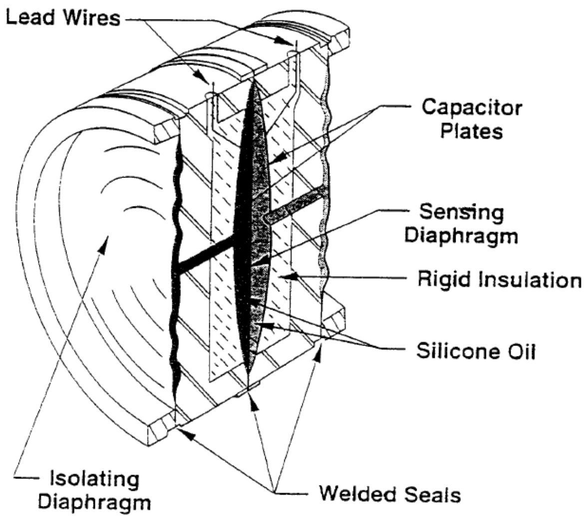


- In differential version, the capacitance of the other one increases and the other one's decreases

- Linearity and stability are good but the measuring electronics is more complicated

Capacitive pressure sensor in practice

- 2 insulator films made of special metal compound
  - Also to measure corrosive materials
- Pressure difference to sensor film via oil
  - Desired permittivity to capacitor
  - Absorbs shocks and vibrations



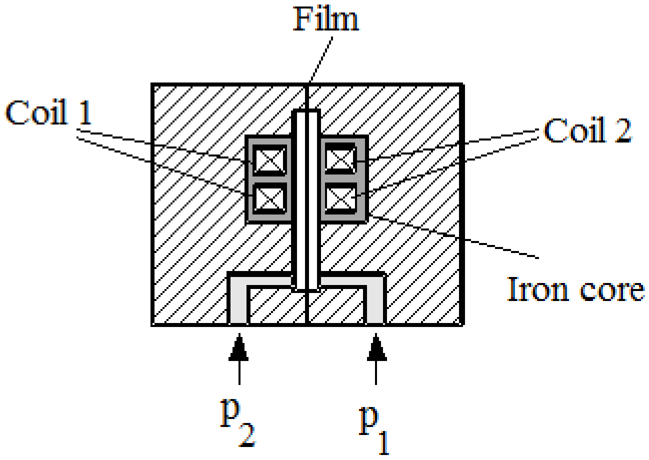
Piezo sensor vs. capacitive sensor

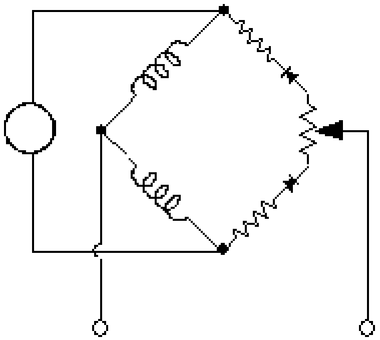
- Films can be protected against overpressure with a mechanical support
  - Movement of a capacitive film is bigger than in piezo sensors (better support is possible)
  - In film based sensors, meter breaks down at pressures 10 times (piezo) and 1000 times (capacitive) higher than the upper limit of the measurement range
- Flatness of the film is important for capacitive sensors
  - Displacements are often smaller that thicknesses
- Capacitive sensors have better relative sensitivity
- Stray capacitance can easily be as big as nominal capacitances (Measuring circuits must be close to sensors!)
- Both have low hysteresis

Inductive (reluctance) pressure sensor

- Change in pressure bends magnetic film
  - Air gap between the iron core and the film changes and, thus, the reluctance also changes
  - Inductance of the coil changes
- Measurements with small displacements (< 30 mm)

  → Small pressures





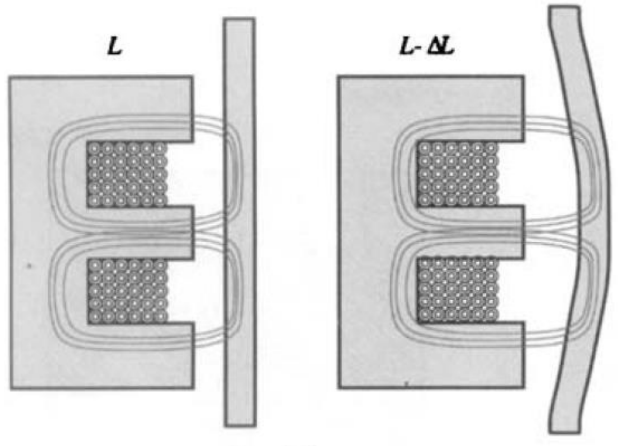
Reluctance sensor

Material i causes a reluctance $R_i = \frac{l_i}{\mu_i A_i}$

$l_i =$ distance experienced by flux in material

$\mu_i =$ permeability of the material

$A_i =$ area in material which is perpendicular to direction of propagation



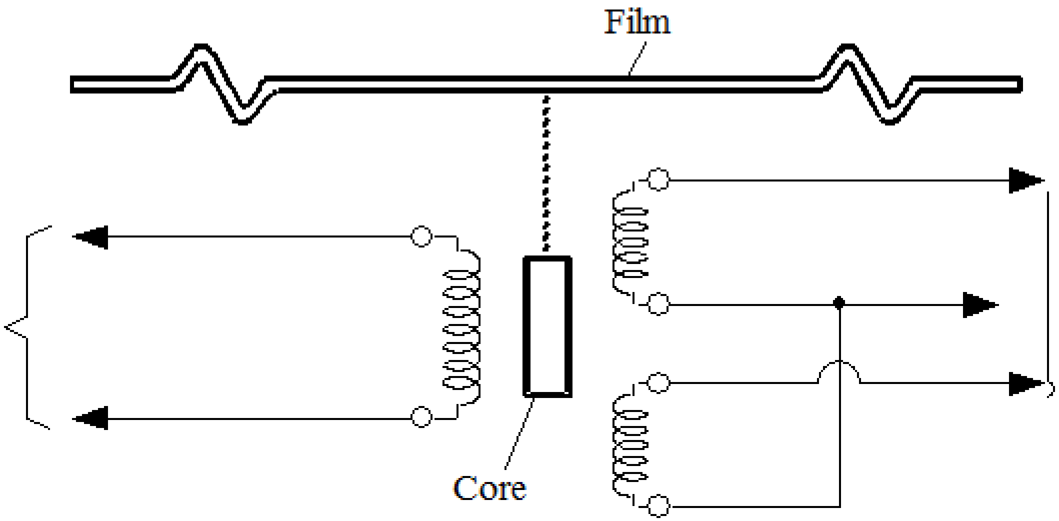
Inductance of a coil, which contains N turns $L = \frac{N^2}{\sum_{i=0}^{M} R_i}$

Pros of reluctance sensor

- Low temperature dependency
- Very small pressure difference measurements
- Due to small pressure cavity, there is good endurance to overpressure (’short circuit’ of the magnetic parts does not disturb)
  - In practice, it almost never breaks down

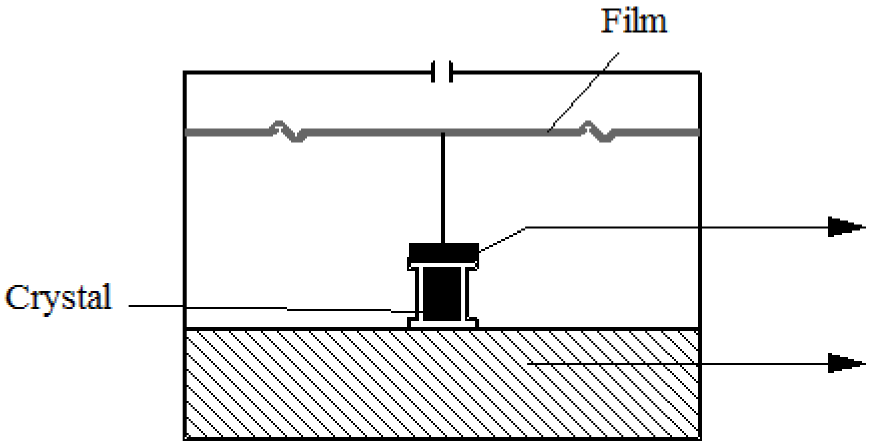
Inductive pressure sensor,
Linear Variable Differential Transformer (LVDT)

- Moving iron core changes the transformer ratio



Piezoelectric pressure sensor

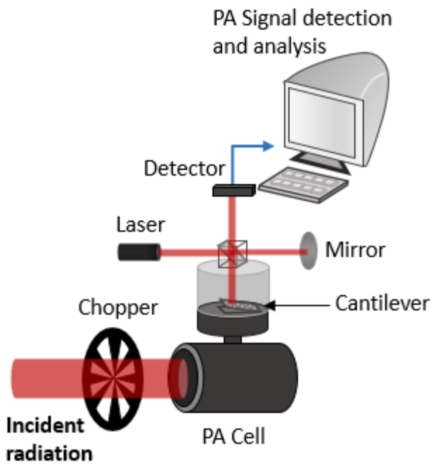
- Electric charge of the crystal surfaces change when the surface is strained
- Leakage currents compensate the charges on the crystal surfaces
  - Not suitable to measure static pressure



Piezoelectric pressure sensor

- Pros
  - High output signal and specific frequency
  - Small size, durable
- Cons
  - High output impedance and temperature sensitivity
  - Requires an amplifier
  - Only dynamic measurement

Cantilever Pressure sensor



Schematic diagram of Photoacoustic radiation detection setup with cantilever pressure sensor.

Absorption of chopped radiation by radiation absorber

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Periodic volume expansion of carrier gas due to heating

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Gaseous pressure induced cantilever movement

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Interferometric detection of cantilever displacement