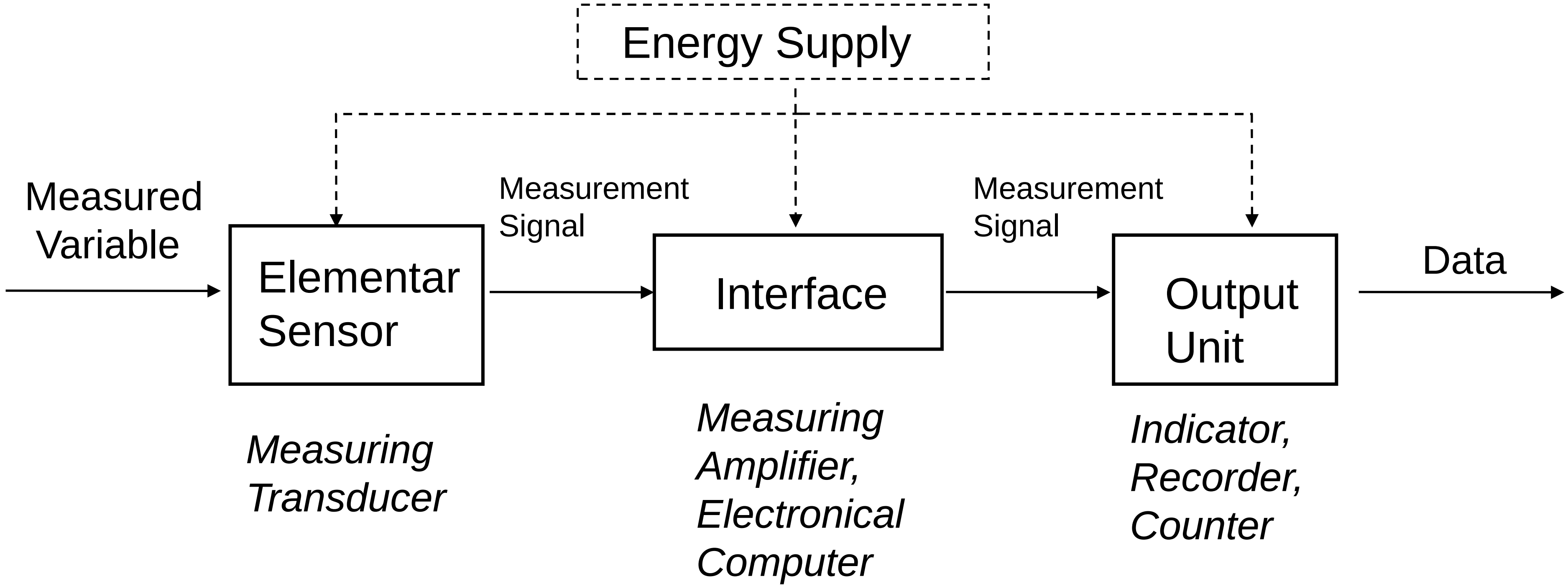
4 Structures of Sensor Systems

4.0 Introduction

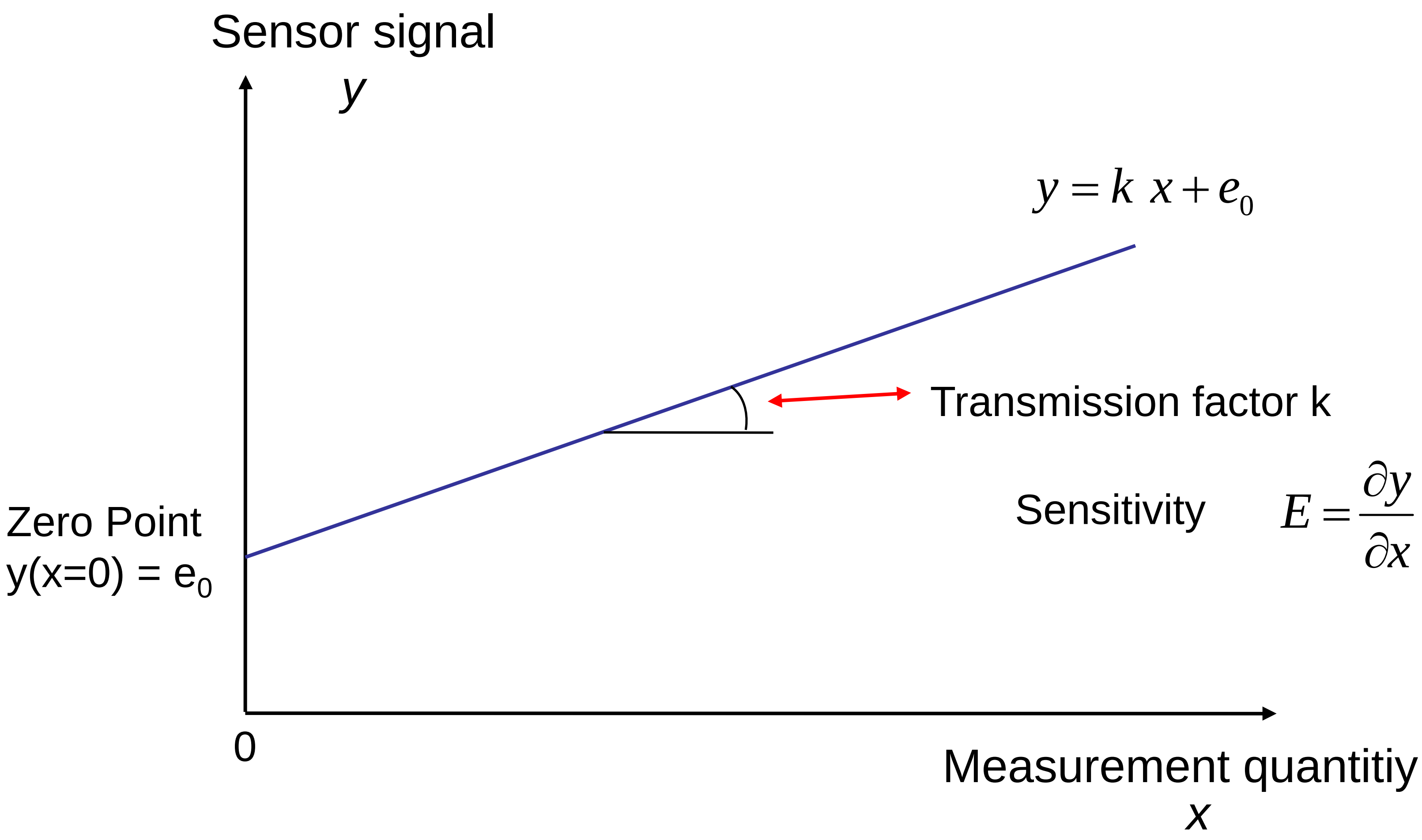
Structure of Measurement Systems

VDI/VDE 2600

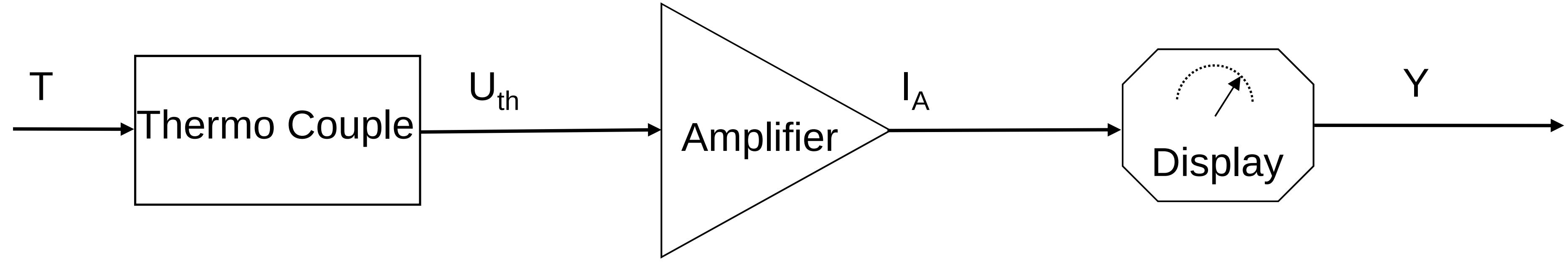


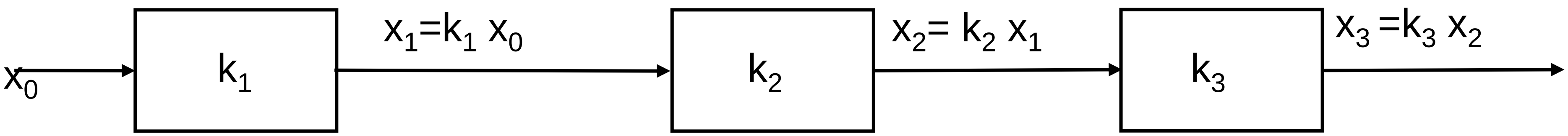
4.0 Introduction

Item: Linear Sensor



4.1 Chain Structure





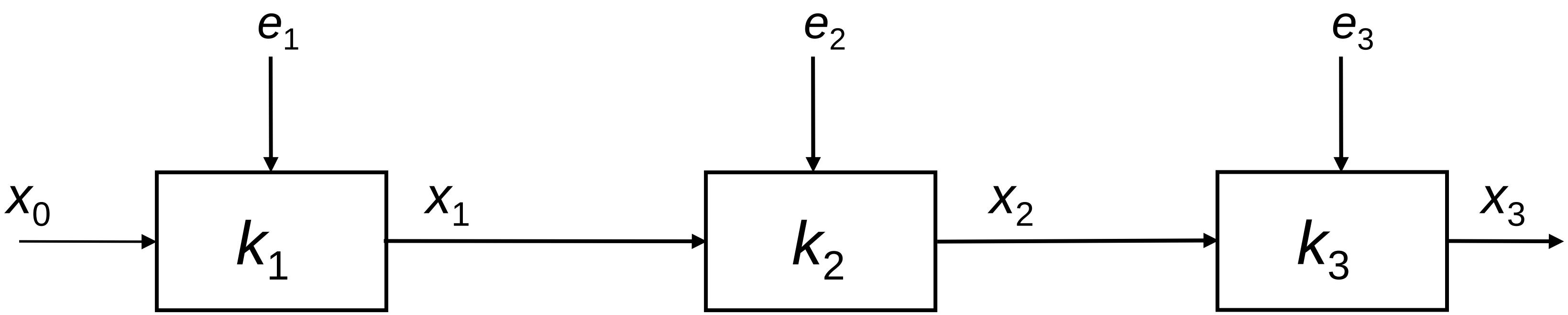
$$\boxed{x_3 = k_3\, k_2\, k_1\, x_0}$$

Multiplicative Deviations: Deviations of transmissions factors

$$x_3 = (k_3 + \Delta k_3)\,(k_2 + \Delta k_2)\,(k_1 + \Delta k_1)\,x_0$$

Error Propagation!!!

4.1 Chain Structure



$$x_1 = k_1\, x_0 + e_1 \qquad x_2 = k_2\,(k_1\, x_0 + e_1) + e_2$$

$$x_3 = [k_2\,(k_1\, x_0 + e_1) + e_2]\, k_3 + e_3$$

$$= k_3 k_2 k_1\, x_0 + k_3 k_2\, e_1 + k_3 e_2 + e_3$$

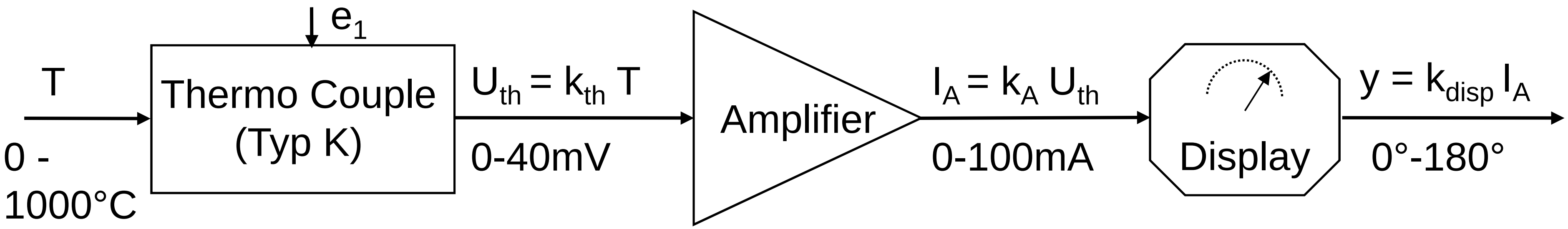
Additive deviations are multiplied by the transmission factors and involve an additional zero-displacement

Temperature Effect

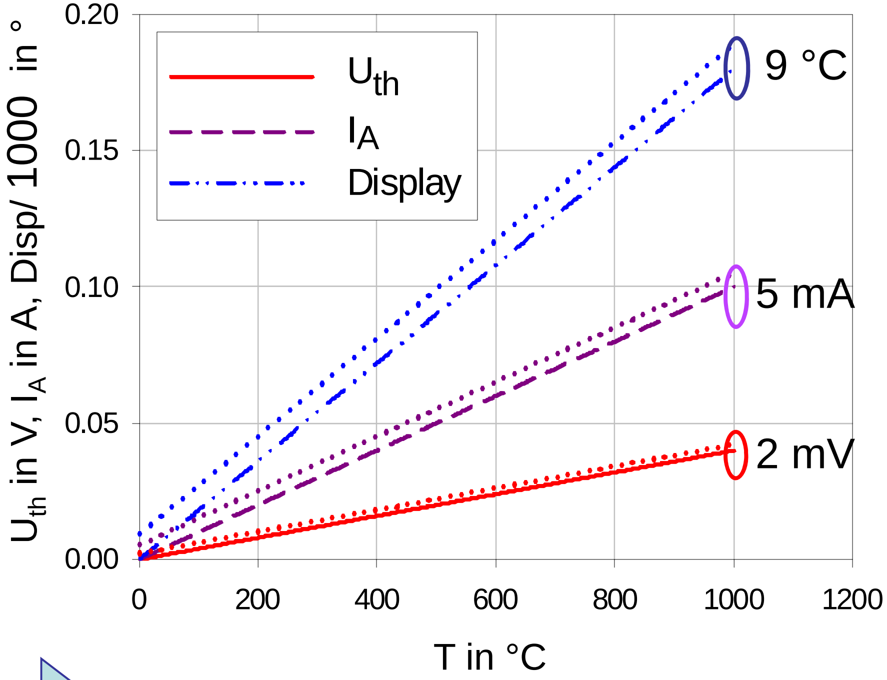
$$x_3 = k_3(T)\, k_2(T)\, k_1(T)\, x_0 + k_3(T)\, k_2(T)\, e_1 + k_3(T) e_2 + e_3$$

Linear dependence of transmission factors of T
→ non-linear dependence of the whole transmission factors of T

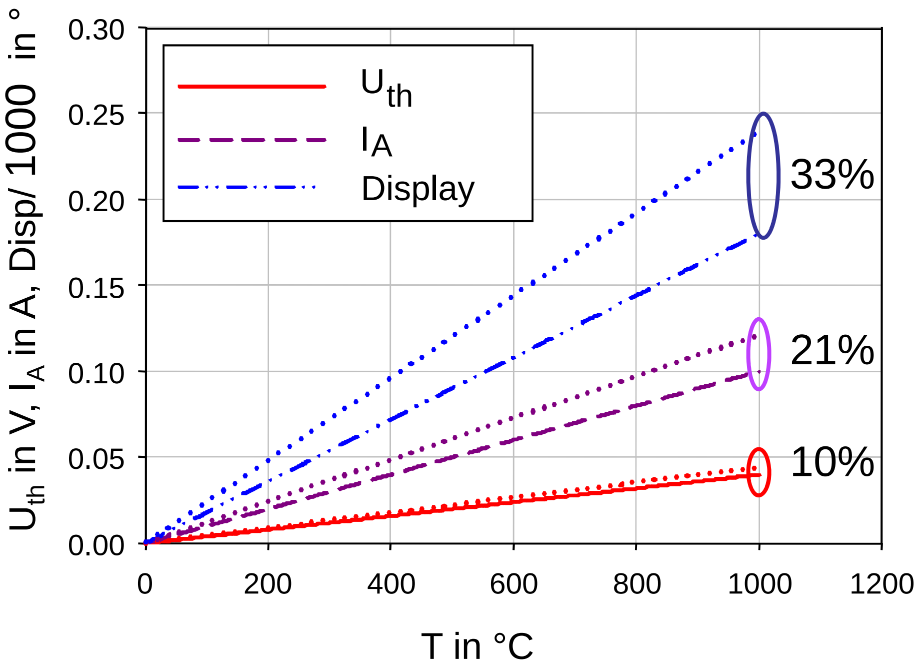
4.1 Chain Structure



2 mV additive deviation at the thermo couple

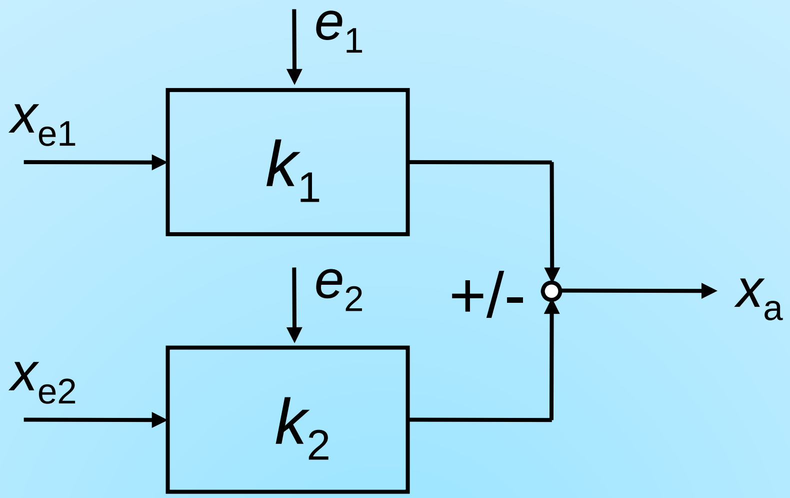


10% deviation of the transmission factors



The chain structure amplifies both multiplicativeand additive errors.

4.2 Parallel Structure



Sensor$_1$ and Sensor$_2$ are identical.

4.2.1 Sum Principle

Both Sensors are exposed to the same input signals X_{e1} and X_{e2}

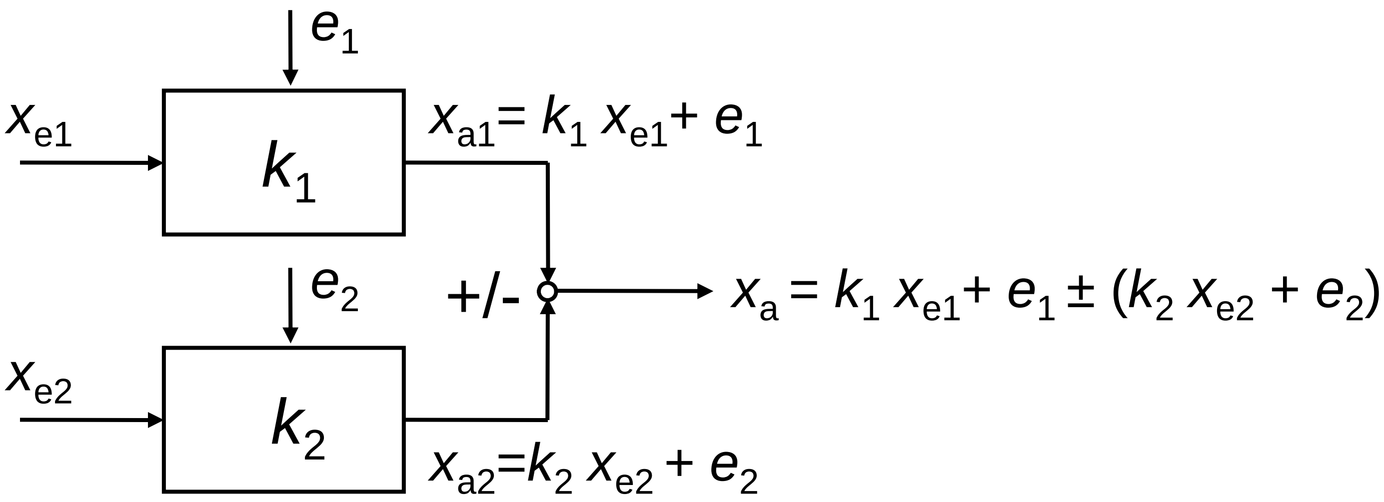
- Calculate the output Signal in the case of the sum principle.
- What is the advantage thereby?

4.2.2 Difference Principle

Both Sensors are exposed to different input signals X_{e1} and X_{e2}

- Calculate the output Signal in the case of the difference principle.
- What is the advantage thereby?

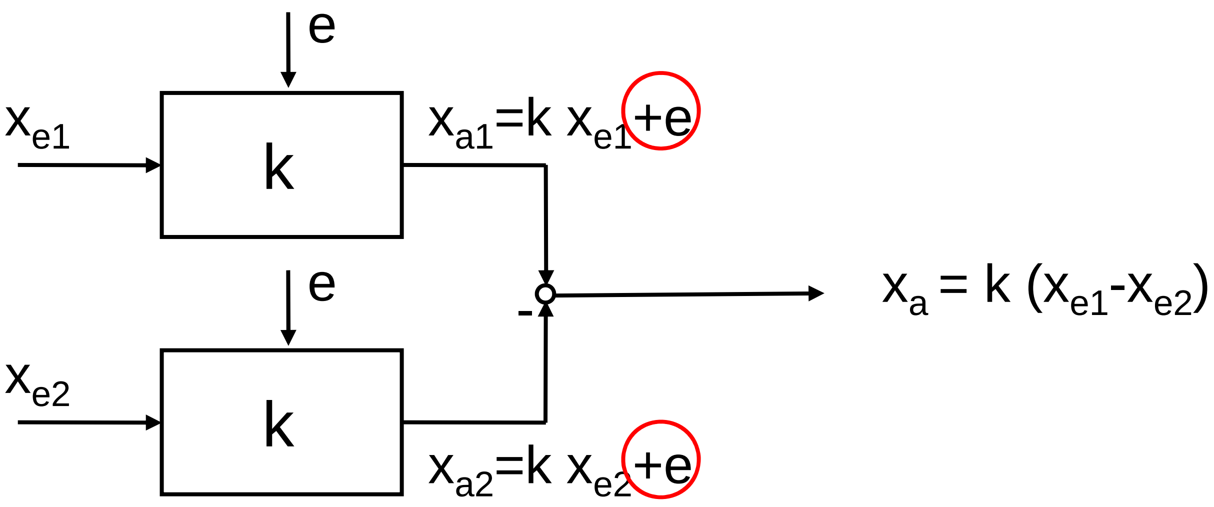
4.2 Parallel Structure



4.2.1 Sum Principle

- Averaging process

4.2.2 Difference Principle



→ Elimination of the zero point

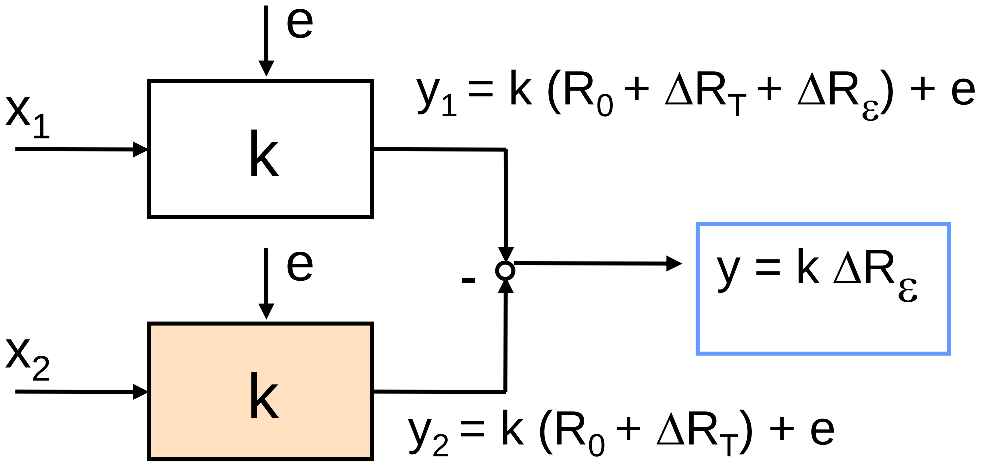
But also generally:

→ Common-mode rejection

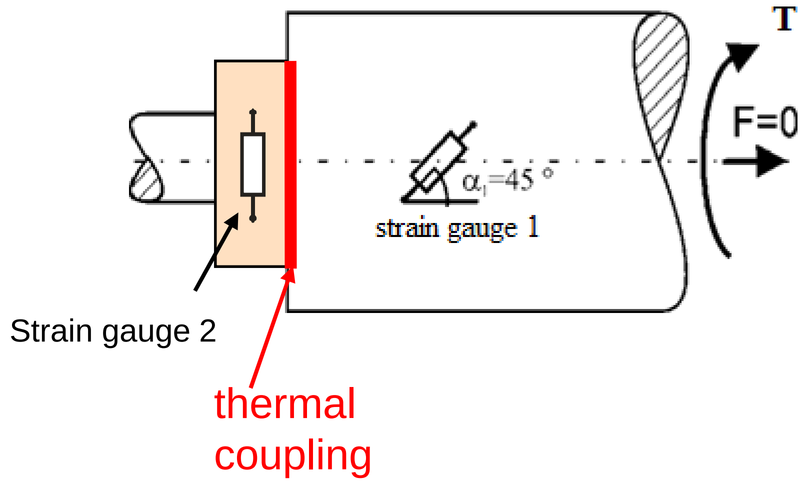
4.2.2 Difference principle
Compensation of Influence Effects

Strain gauge with the basic resistance R_0

- Extensions ε
- Temperature T



Torque Measurement
with strain gauge

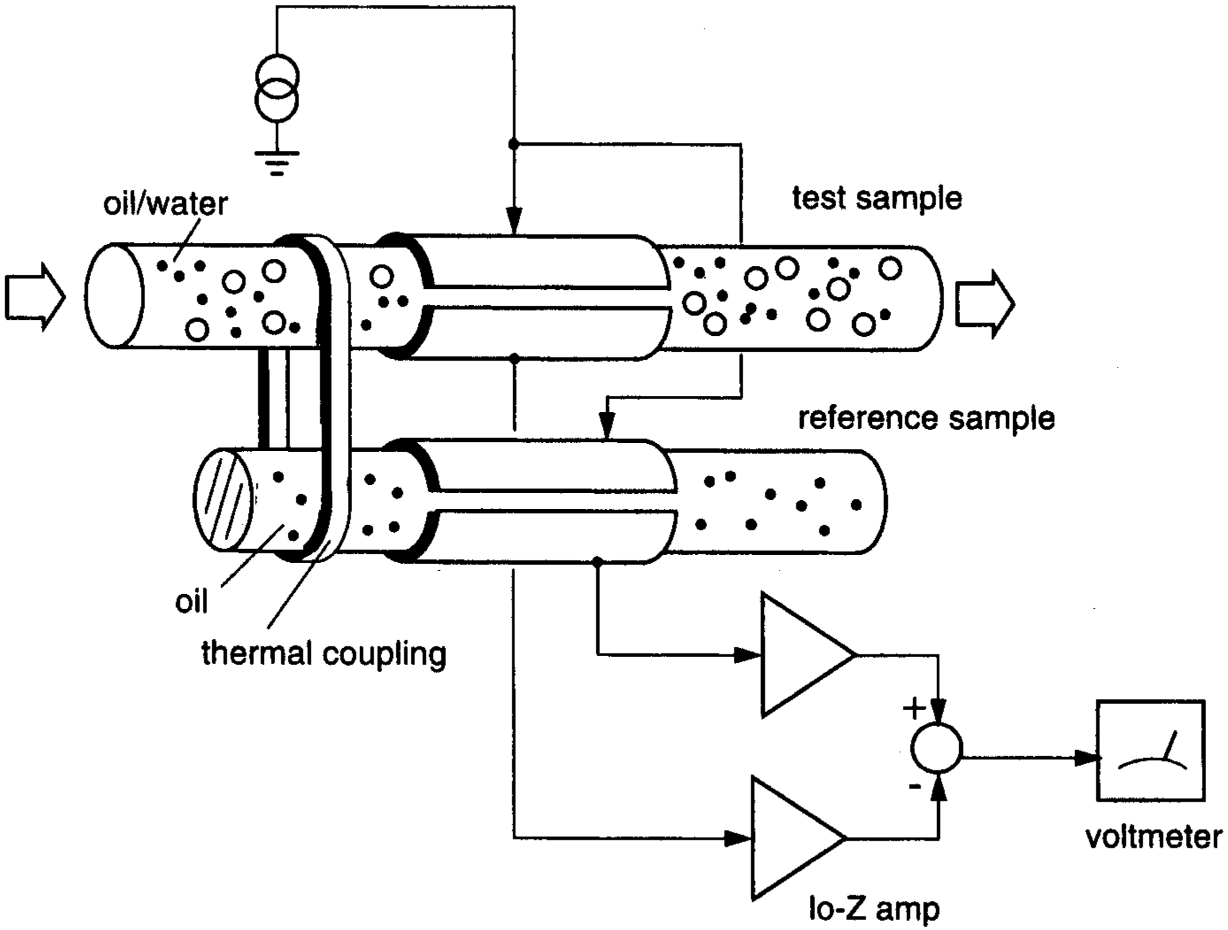


Compensation of temperature effect

4.2.2 Difference principle

Compensation of Influence Effects

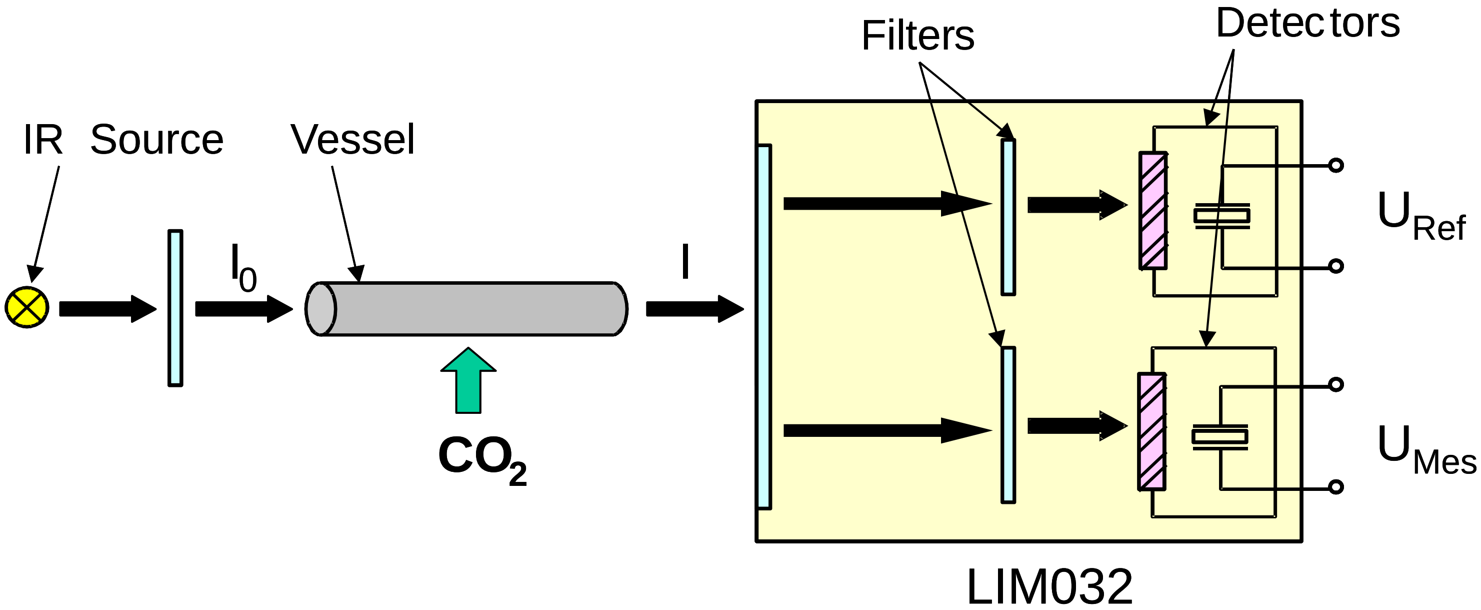
Example: Capacitive Measurement of Water Volume in Oil



4.2.2 Difference principle

Example: NDIR CO_2-Sensor

LIM032, InfraTec GmbH

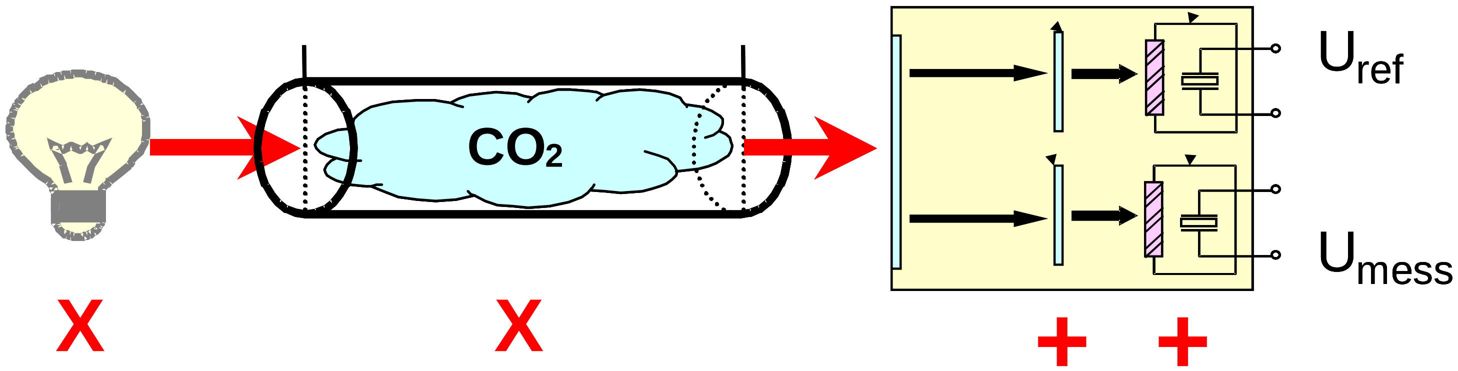


[O. Zhelondz 2006]

4.2.2 Difference principle

Example: NDIR CO_2-Sensor

Effects on Measurement and Reference Signal



<u>Multiplicative effects</u>

Changes in radiation intensity

(Ageing, Pollution)

Temperature dependence of radiation intensity

Temperature and pressure dependence of absorption processes

<u>Additive effects</u>

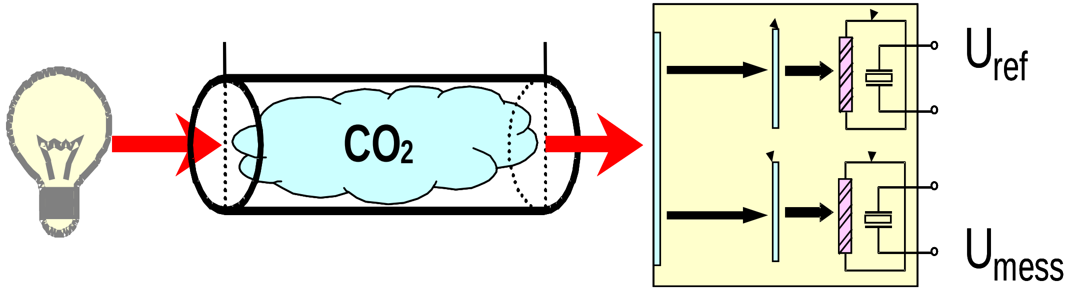
Temperature drift of filter

Temperature drift of the pyrodetector

4.2.2 Difference principle

Example: NDIR CO_2-Sensor

Elimination of Undesired Effects (1)



$$U_{ref} = k \cdot I + a$$

$$U_{Meas} = k \cdot I \cdot e^{-\varepsilon \cdot x_{CO2} \cdot L_V} + a$$

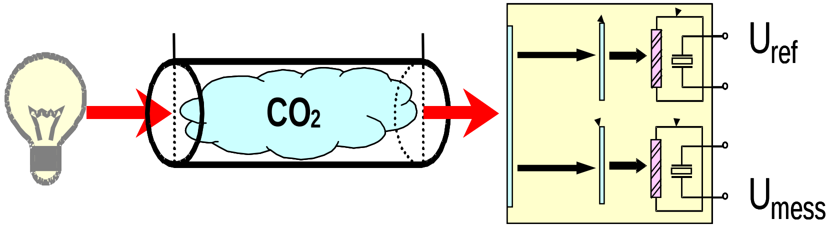
$$U_{Meas} - U_{ref} = k \cdot I \cdot \left(e^{-\varepsilon \cdot x_{CO2} \cdot L_V} - 1\right)$$

Elimination of additive effects

$$\frac{U_{Meas}}{U_{ref}} = \frac{e^{-\varepsilon \cdot x_{CO2} \cdot L_V} + \dfrac{a}{k \cdot I}}{1 + \dfrac{a}{k \cdot I}}$$

Declination of multiplicative effects

4.2.2 Difference principle
Example: NDIR CO_2-Sensor
Elimination of Undesired Effects (2)



$$U_{ref} = k \cdot I + a$$

$$U_{Meas} = k \cdot I \cdot e^{-\varepsilon \cdot x_{CO2} \cdot L_V} + a$$

if $a \approx 0$

$$\log(U_{Meas}) - \log(U_{ref}) = \log(k \cdot I) - \varepsilon \cdot x_{CO2} \cdot L_V - \log(k \cdot I)$$
$$= -\varepsilon \cdot x_{CO2} \cdot L_V$$

- Declination of multiplicative effects
- Linearization

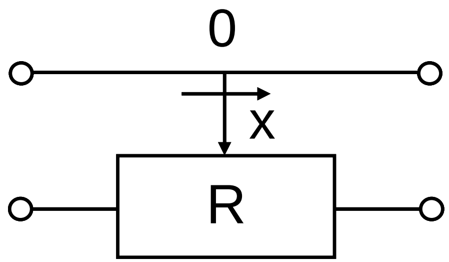
$$\frac{U_{Meas} - U_{ref}}{U_{ref} - a} = \frac{k \cdot I \cdot e^{-\varepsilon \cdot x_{CO2} \cdot L_V} - k \cdot I}{k \cdot I} = e^{-\varepsilon \cdot x_{CO2} \cdot L_V} - 1$$

- Elimination of multiplicative effects

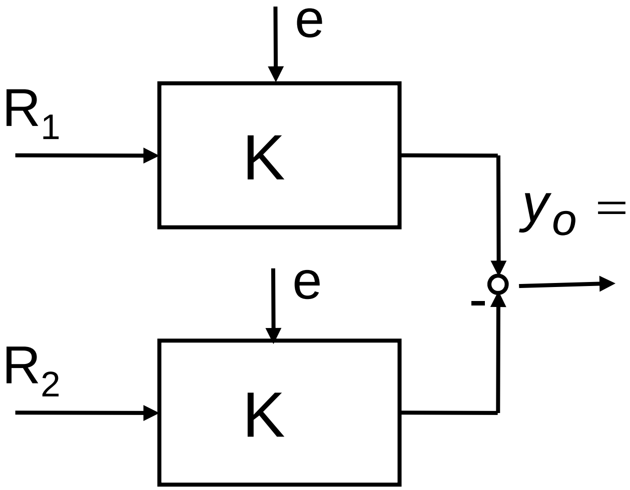
4.2.3 Differential Principle

Inverse dependence!

$$R_1 = \left(\frac{R}{2} + \Delta R(x)\right)$$



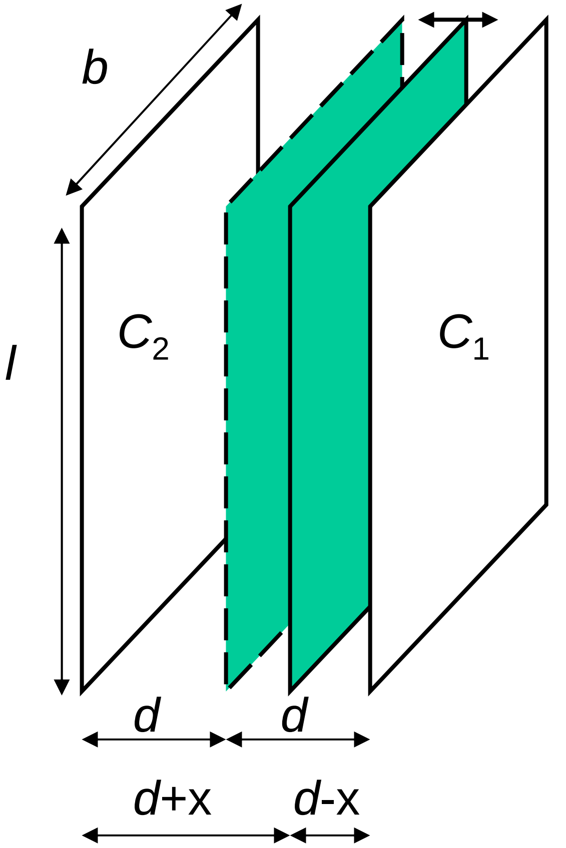
$$R_2 = \left(\frac{R}{2} - \Delta R(x)\right)$$



$$y_o = k\left(\frac{R}{2} + \Delta R(x)\right) + e - k\left(\frac{R}{2} - \Delta R(x)\right) - e = 2k\,\Delta R(x)$$

Advantages:
- Common-mode rejection
- Increase of sensibility

4.2.3 Differential Principle
Example: Differential Capacitive Measurement



x: Displacement

$$C_1 - C_2 = \varepsilon_r \varepsilon_0 \frac{l \cdot b}{(d-x)} - \varepsilon_r \varepsilon_0 \frac{l \cdot b}{(d+x)}$$

$$= 2\varepsilon_r \varepsilon_0 \frac{l \cdot b \cdot x}{\left(d^2 - (x)^2\right)}$$

$$C_1 + C_2 = \varepsilon_r \varepsilon_0 \frac{l \cdot b}{(d-x)} + \varepsilon_r \varepsilon_0 \frac{l \cdot b}{(d+x)}$$

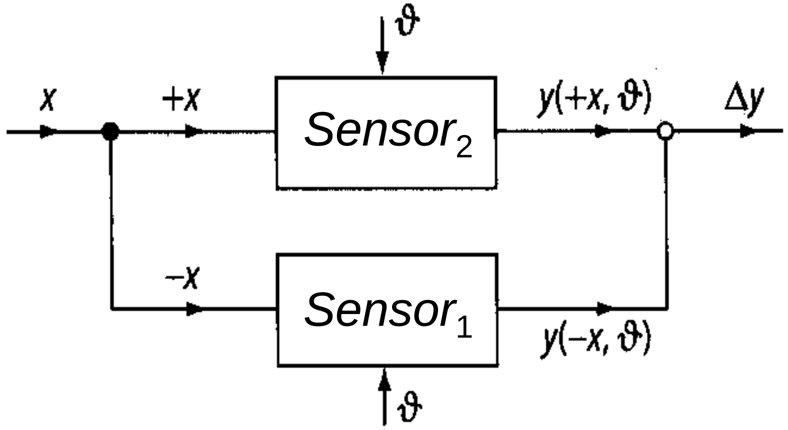
$$= 2\varepsilon_r \varepsilon_0 \frac{l \cdot b \cdot d}{\left(d^2 - x^2\right)}$$

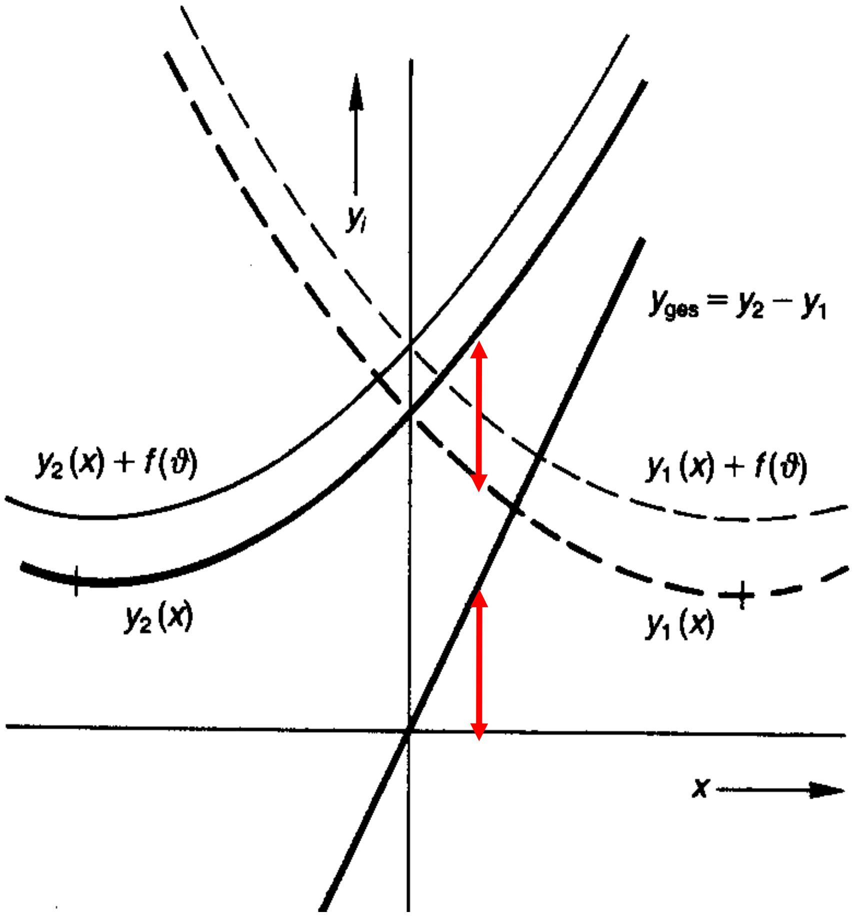
$$\frac{C_1 - C_2}{C_1 + C_2} = \frac{x}{d} \qquad x = d\frac{C_1 - C_2}{C_1 + C_2}$$

Advantages:
- Common mode rejection
- Independent on geometry

4.2.3 Differential Principle

Linearization with parallel structure and differential principle





$$y_1 = a_0 + a_1(x_0 - x) + a_2(x_0 - x)^2 + f(\vartheta)$$

$$y_2 = a_0 + a_1(x_0 + x) + a_2(x_0 + x)^2 + f(\vartheta)$$

$$\Rightarrow \quad y_{total} = y_2 - y_1 = 2(a_1 + 2\, a_2\, x_0)\, x$$

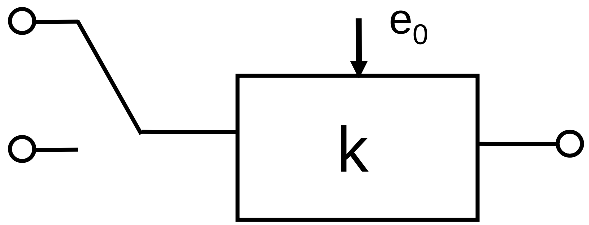
Advantages:
- common-mode rejection!
- linearization

4.2.4 Reference Principle

Zero point $x_{e1} = 0$

Measured variable $x_{e2} = x$

Reference value $x_{e3} = x_r$



$x_{a1} = e_0$

$x_{a2} = k\,x + e_0$

$x_{a3} = k\,x_r + e_0$

$$x_{a2} - x_{a1} = k\,x$$

$$x_{a3} - x_{a1} = k\,x_r$$

$$\frac{x_{a2} - x_{a1}}{x_{a3} - x_{a1}} = \frac{k\,x}{k\,x_r} = \frac{x}{x_r}$$

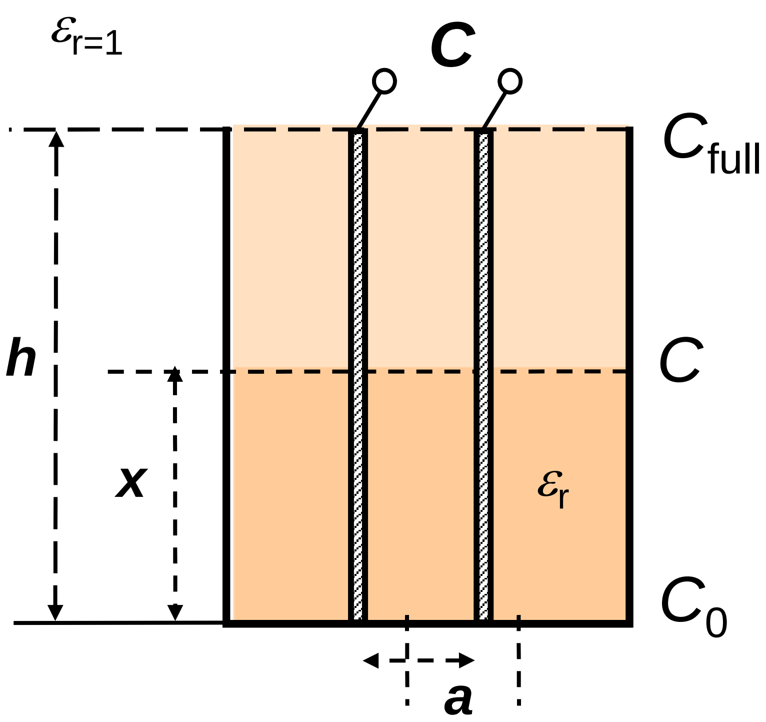
$$x = x_r\,\frac{x_{a2} - x_{a1}}{x_{a3} - x_{a1}}$$

Advantages:
- common-mode rejection
- elimination of multiplicative errors

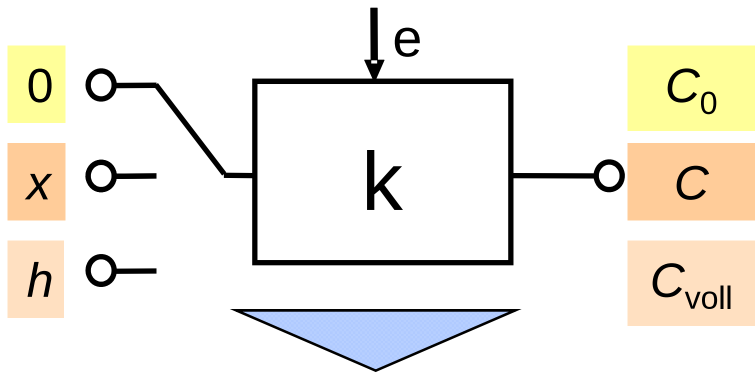
4.2.4 Reference Principle

Example: capacitive level measurement after the reference principle

$$C = C_{air} + C_{liquid} = \underbrace{\boxed{\left[\varepsilon_0 \frac{w}{a}(\varepsilon_r - 1)\right]}}_{k}\, x + \underbrace{\boxed{\varepsilon_0 \frac{w}{a} h}}_{e}$$



w: width of capacitor plates



$$C_0 = \varepsilon_0 \frac{w}{a} h$$

$$C_{full} = \varepsilon_0 \varepsilon_r \frac{w}{a} h$$

$$x = h \cdot \frac{C - C_0}{C_{full} - C_0}$$

suppression of:

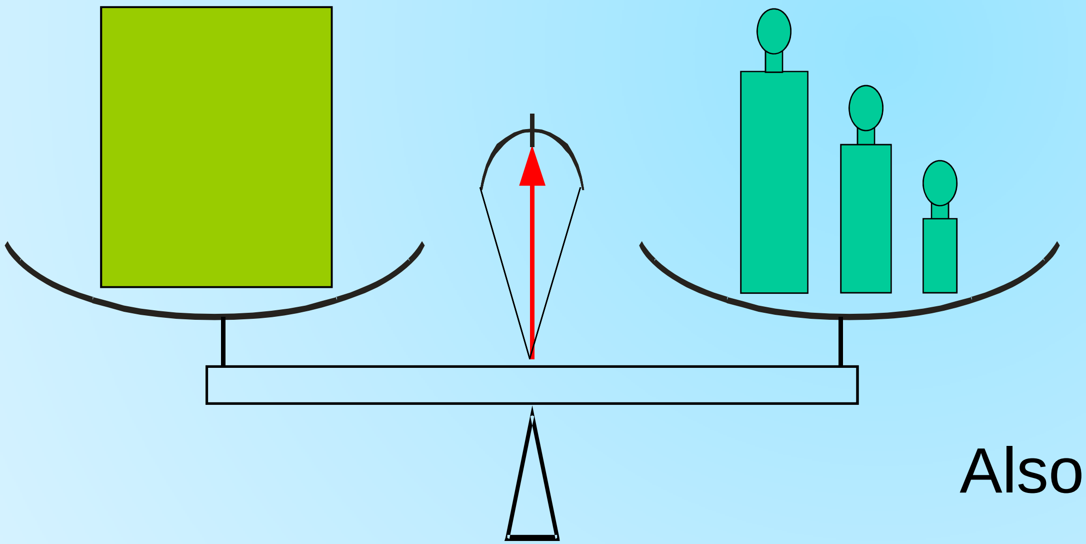
- *Additive errors e*
- *Multiplicative errors k*

Possibility for self-tests

4.3 Closed Loop Structure

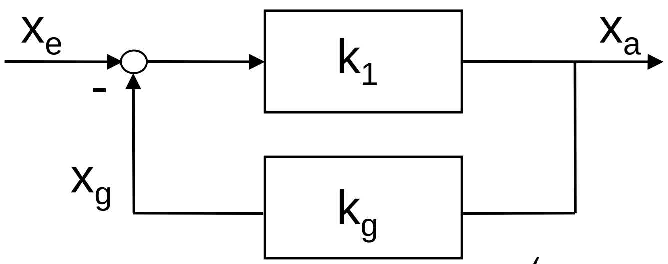
also called null mode or compensation method

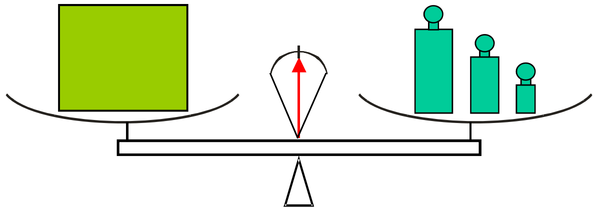
Why are small weight differences detectable?



Also for Gold and Diamond !

4.3 Closed Loop Structure





$$x_a = k_1\left(x_e - x_g\right) = k_1\left(x_e - k_g x_a\right)$$

$$x_a = \frac{k_1}{1+k_1 k_g} x_e = \frac{1}{\frac{1}{k_1}+k_g} x_e \approx \frac{1}{k_g} x_e \quad for\ k_1 \to \infty$$

Advantages:

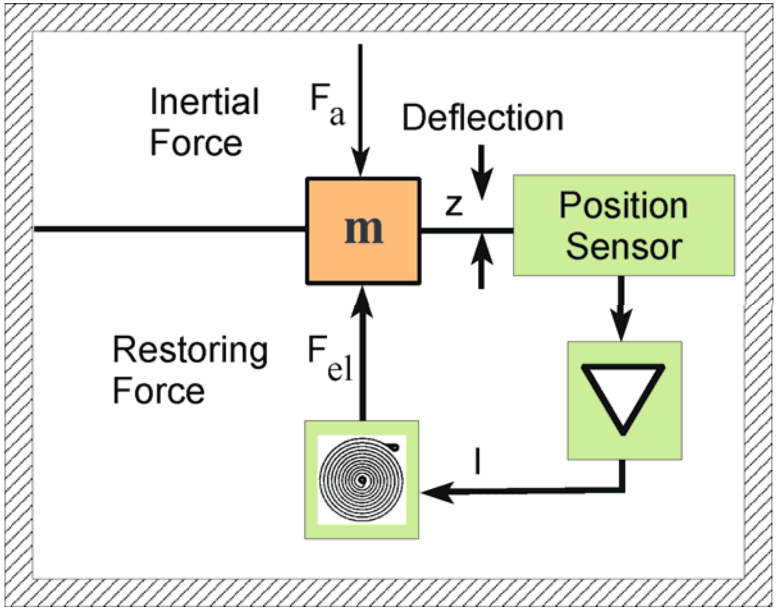
- Precision more dependent on k_g
- Suitable for small changes of sensor signal
- Measurement without influence on the measured quantity

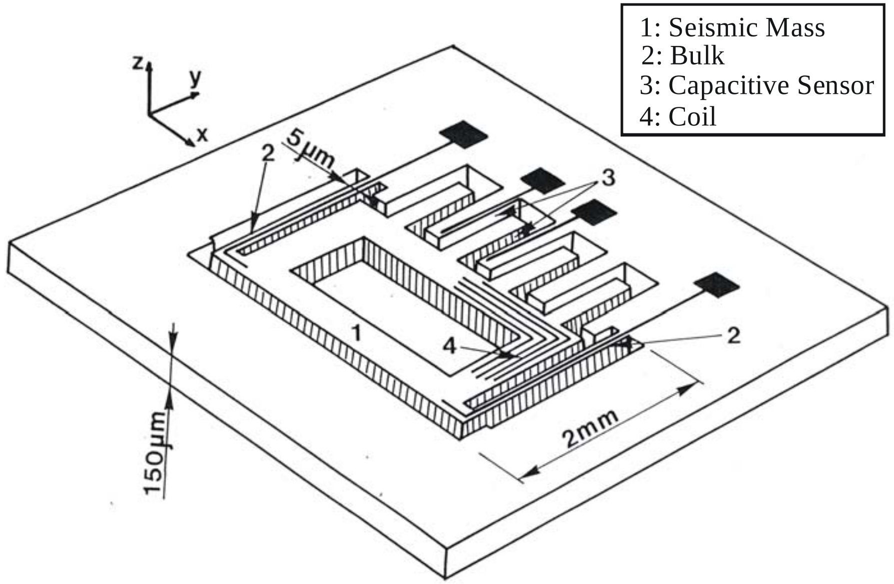
Disadvantages:

- Stability consideration necessary!
- Dynamic is dependent on the inverse feedback

4.3 Closed Loop Structure

Example: Acceleration Sensor



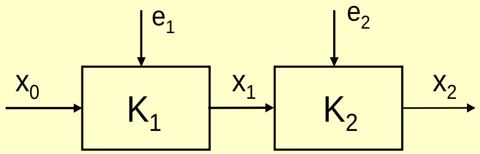


[LETI, Grenoble]

Prof. Dr.-Ing. O. Kanoun
Chair for Measurement and Sensor Technology
P. 4-23

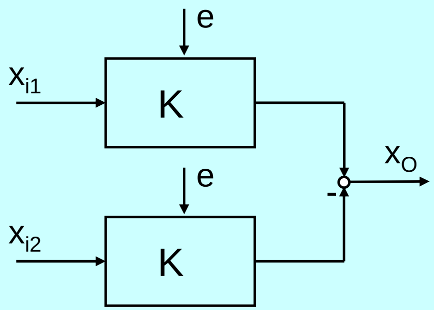
4.1-4.3 Chain-, Parallel and Closed Loop Structure

Chain Structure



- Often used
- Additive and multiplicative errors are Amplified

Parallel Structure

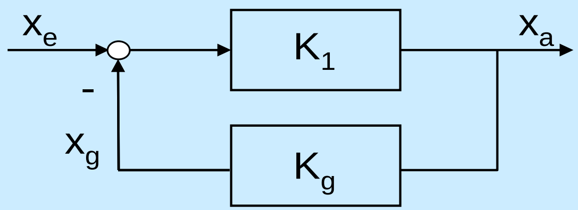


Common Mode Rejection

⇨ Differential measurement
- higher sensitivity

⇨ Reference measurement
- Elimination of multiplicative errors
- Possibility of Self-Tests

Closed Loop Structure



- High Stability
- Suitable for small changes of sensor signal
- High precision
- Possibility of Self-Tests
- Sensor dynamic