Sensors I

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Temperature

- Thermodynamic status quantity given by the mean kinetic energy of molecules movement.
- The basic unit: degree Kelvin [°K],
- Often used unit: degree Celsius [°C]
  - 1°K=1 °C, 0 °K=cca.-273,15 °C

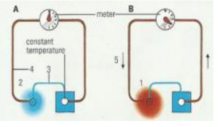
Temperature sensors

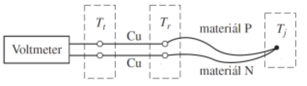
- Contacted measurement
  - Thermocouple (the most widely used)
  - Resistive
    - metal
    - Semiconductor without PN junction
  - PN junction (simple component, integrated circuit)
  - Contactless systems
    - Pyrometers
    - Thermovision (the most complex device with the most complex infomation)

Thermocouple principle

- Seebeck thermoelectric effect: if metallic wire has different temperature at its ends, the thermoelectric voltage is generated between the wire end with value $U_{AB} = \int_{T_A}^{T_B} \sigma(T)dT$
- σ is the Seebeck coeficient, which depends from wire material (metal) and difference of temperatures but not from geometric dimensions of wire.
- Thermocouple: junction of two wire from different materials (different σ), connected at one end. The other ends are used as output of thermocouple for sensing generated thermoelectric voltage:

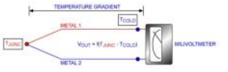
$$U = \int_{T_r}^{T_j} \sigma_P(T)dT - \int_{T_r}^{T_j} \sigma_N(T)dT = \int_{T_r}^{T_j} [\sigma_P(T) - \sigma_N(T)]dT = \int_{T_r}^{T_j} \sigma_{PN}(T)dT$$

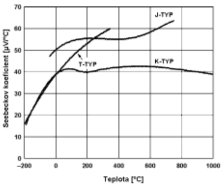




Thermocouple property

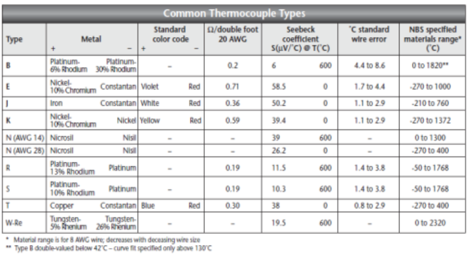
- Thermocouple always gives voltage expressing the difference of temperatures between the ends of thermocouple (the place with unknown measured temperature and temperature of thermocouple terminals).
  - If we want to measure the temperature in degree Celsius, the thermocouple output must have the temperature = 0◦C (technology problem)
- σ_{PN} [μV/°C] is the relative Seebeckov coefficient of thermocouple, dependent from temperature (!) ⇒ relation between thermocouple output voltage and difference of temperatures is non-linear function





Thermocouple types

The most common types



Common Thermocouple Types

	Type	Metal +	Metal –	Standard color code +	Standard color code –	Ω/double foot 20 AWG	Seebeck coefficient S(μV/°C)	@ T(°C)	°C standard wire error	NBS specified materials range* (°C)
	B	Platinum-6% Rhodium	Platinum-30% Rhodium	–		0.2	6	600	4.4 to 8.6	0 to 1820**
*	E	Nickel-10% Chromium	Constantan	Violet	Red	0.71	58.5	0	1.7 to 4.4	-270 to 1000
*	J	Iron	Constantan	White	Red	0.36	50.2	0	1.1 to 2.9	-210 to 760
*	K	Nickel-10% Chromium	Nickel	Yellow	Red	0.59	39.4	0	1.1 to 2.9	-270 to 1372
	N (AWG 14)	Nicrosil	Nisil	–		–	39	600	–	0 to 1300
	N (AWG 28)	Nicrosil	Nisil	–		–	26.2	0	–	-270 to 400
	R	Platinum-13% Rhodium	Platinum	–		0.19	11.5	600	1.4 to 3.8	-50 to 1768
	S	Platinum-10% Rhodium	Platinum	–		0.19	10.3	600	1.4 to 3.8	-50 to 1768
*	T	Copper	Constantan	Blue	Red	0.30	38	0	0.8 to 2.9	-270 to 400
	W-Re	Tungsten-5% Rhenium	Tungsten-26% Rhenium	–		–	19.5	600	–	0 to 2320

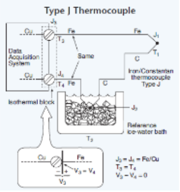
* Material range is for 8 AWG wire; decreases with deceasing wire size
** Type B double-valued below 42°C – curve fit specified only above 130°C

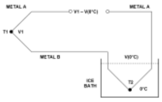
Measurement by the thermocouple

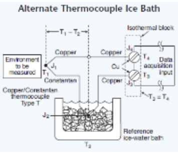
- Advantages:
  - Wide range of temperatures
  - Fast reaction (small size), resistance again mechanical vibration
  - Simple construction, proper also for dangerous environment
- Disadvantages:
  - Small output voltage (disturbance, noise)
  - Complex conversion from voltage to temperature (hardware or software compensation is needed
  - Rusting (corrosion)

HW Compensation

- Hardware
  - Two, the same thermocouples connected in series with opposite voltage direction, one is on reference temperature
  - Connection from TC output to Cu wire on isothermal connection block - error voltage are substracted.
  - Measure final voltage and calculation temperature from the compensated voltage

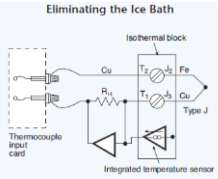

Type J Thermocouple

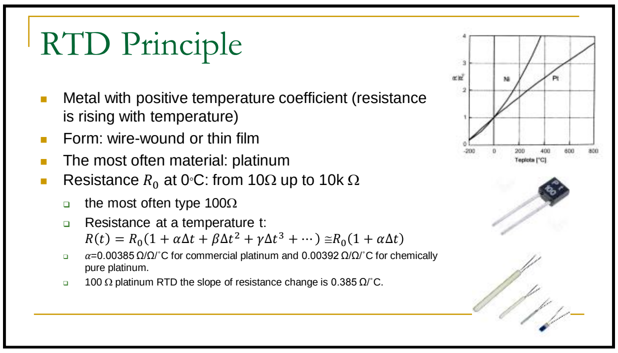



Alternate Thermocouple Ice Bath

SW Compensation

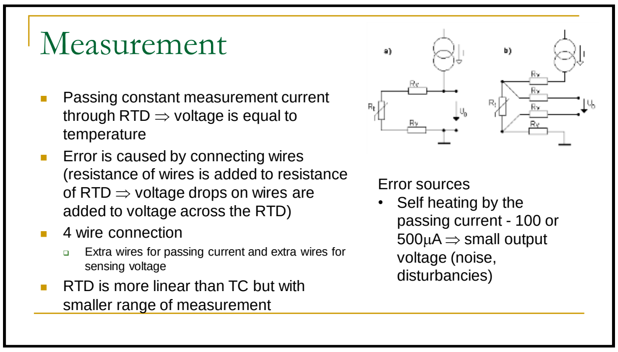
- Software:
  - Measurement of temperature of connector block
  - Calculation of offset voltage for the given TC
  - Subtraction of the calculated offset from measured TC voltage
  - Calculation temperature from the compensated voltage


Eliminating the Ice Bath



RTD Principle

- Metal with positive temperature coefficient (resistance is rising with temperature)
- Form: wire-wound or thin film
- The most often material: platinum
- Resistance R_0 at 0◦C: from 10Ω up to 10k Ω
  - the most often type 100Ω
  - Resistance at a temperature t: $R(t) = R_0(1 + \alpha\Delta t + \beta\Delta t^2 + \gamma\Delta t^3 + \cdots) \cong R_0(1 + \alpha\Delta t)$
  - α=0.00385 Ω/Ω/˚C for commercial platinum and 0.00392 Ω/Ω/˚C for chemically pure platinum.
  - 100 Ω platinum RTD the slope of resistance change is 0.385 Ω/˚C.

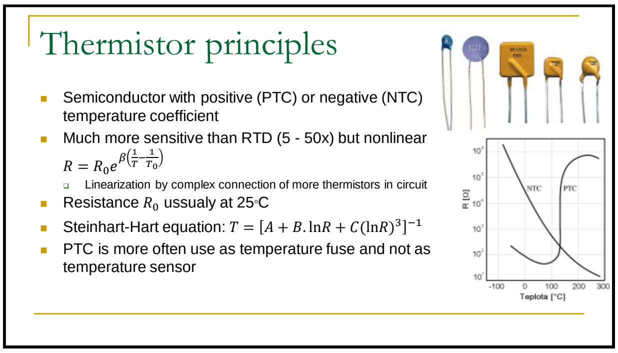


Measurement

- Passing constant measurement current through RTD ⇒ voltage is equal to temperature
- Error is caused by connecting wires (resistance of wires is added to resistance of RTD ⇒ voltage drops on wires are added to voltage across the RTD)
- 4 wire connection
  - Extra wires for passing current and extra wires for sensing voltage
- RTD is more linear than TC but with smaller range of measurement

Error sources

- Self heating by the passing current - 100 or 500μA ⇒ small output voltage (noise, disturbancies)

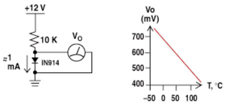


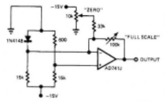
Thermistor principles

- Semiconductor with positive (PTC) or negative (NTC) temperature coefficient
- Much more sensitive than RTD (5 - 50x) but nonlinear $R = R_0 e^{\beta\left(\frac{1}{T} - \frac{1}{T_0}\right)}$
  - Linearization by complex connection of more thermistors in circuit
- Resistance R_0 ussualy at 25◦C
- Steinhart-Hart equation: $T = [A + B.\ln R + C(\ln R)^3]^{-1}$
- PTC is more often use as temperature fuse and not as temperature sensor

PN junction

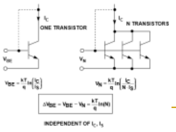
- Voltage on PN junction of diode:
  $U_D = nU_T \ln\left(\frac{I_D}{I_S}\right), \quad U_T = \frac{kT}{q}$
  - More-less linear dependence
- High sensitivity (about -2mV/ ˚C)

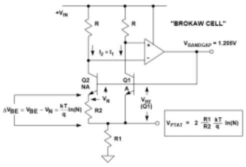




Integrated temperature sensors

- PN junction = Base - Emitter of transistor:
  - Brokaw cell output voltage is independent from currents
- Output signal: DC voltage, current, pulse train, etc.
- Example of integrated circuits LM35 (10mV/°C), AD590 (1uA/°C), SMT160-30, etc.



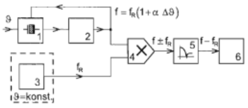


Temperature sensor comparison

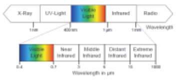
THERMOCOUPLE	RTD	THERMISTOR	SEMICONDUCTOR
Widest Range: –184°C to +2300°C	Range: –200°C to +850°C	Range: 0°C to +100°C	Range: –55°C to +150°C
High Accuracy and Repeatability	Fair Linearity	Poor Linearity	Linearity: 1°C Accuracy: 1°C
Needs Cold Junction Compensation	Requires Excitation	Requires Excitation	Requires Excitation
Low-Voltage Output	Low Cost	High Sensitivity	10mV/K, 20mV/K, or 1μA/K Typical Output

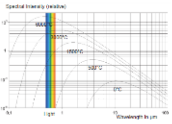
Quartz thermometer

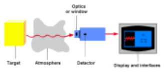
- Resonance frequency of quartz depend from temperature
- Measurement: comparison of two quartz oscillator frequencies
  - Reference in thermostat
  - Other in measured environmental
- Temperature range: from about -80°C up to +250°C with resolution up to 10^{-4} °C



Contact-less temperature measurement

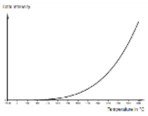






Infrared radiation transports energy. This radiated energy is used to help determine the temperature of a body being measured.

When measuring with pyrometers the intensity of radiation is changed into an electric signal. The intensity of radiation across a convenient spectral band gives the temperature.



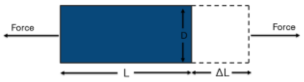
Pyrometer - measures temperature at a spot by detection of infrared light

Infrared camera - matrix of pyrometers creating temperature map of object

STRAIN MEASUREMENTS

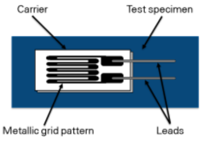
What is strain?

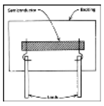
- The amount of deformation a material experiences due to an applied force is called strain.
- Strain ε is defined as the ratio of the change in length of a material to the original, unaffected length, $\varepsilon = \frac{\Delta L}{L}$
- Strain can be positive (tensile), due to elongation, or negative (compressive), due to contraction.
- When a material is compressed in one direction, the tendency to expand in the other two directions perpendicular to this force is known as the Poisson's effect.
- Poisson's ratio (v), is the measure of this effect and is defined as the negative ratio of strain in the transverse direction to the strain in the axial direction.



Strain gage

- Resistive sensor to measure the strain
- Resistance is changed according to deformation (external force, pressure, tension, acceleration, etc.)
- Application: measurement of wage, position, movement, length, …

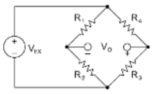




Strain gage – basic parameters

- Material – metal wire or folia (less sensitive and linear), semiconductor (more sensitive, nonlinear)
- The basic parameter:
  - Gage Factor – fractional change in resistance divided by the strain $GF = \frac{\Delta R / R_G}{\varepsilon}$
  - ΔR absolute change of resistance, R_G resistance without a strain, ε mechanical strain
- Usually connected in Weatson brige:
  - 1, 2, or 4 gauges – higher sensitivity
  - General problem: the resistance of connecting wire (R_L)

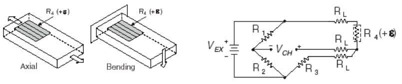
See also http://www.ni.com/white-paper/3642/en/



$$V_O = \left[\frac{R_3}{R_3 + R_4} - \frac{R_2}{R_1 + 2}\right] * V_{EX}$$

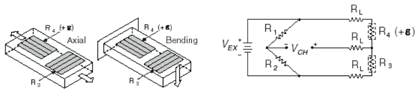
Quarter-bridge Strain gauge

- Measures axial or bend strain
- Type I – (measures axial or bend strain) only single active strain gauge,



$$strain\ (\varepsilon) = \frac{-4V_r}{GF(1+2V_r)} \times \left(1+\frac{R_L}{Rg}\right)$$

- Typ II – one active and one passive strain gauge (compensation of temperature)

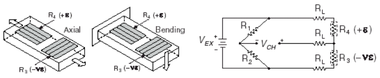


$$strain\ (\varepsilon) = \frac{-4V_r}{GF(1+2V_r)} \times \left(1+\frac{R_L}{Rg}\right)$$

Half bridge strain gage

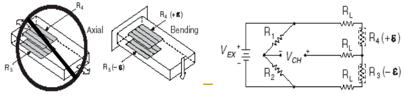
Poisson's effect – if a material were deformed by a force in one dimension, the deformations are present also in other dimensions.

- Type I (axial or bend) – R3 compesates Poisson's effect



$$strain\ (\varepsilon) = \frac{-4V_r}{GF[(1+\nu)-2V_r(\nu-1)]} \times \left(1+\frac{R_L}{R_g}\right)$$

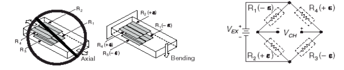
- Type typ II – (measures ONLY bend) combination of measurements both compressive and tensile strains increases



$$strain\ (\varepsilon) = \frac{-2V_r}{GF} \times \left(1+\frac{R_L}{R_g}\right)$$

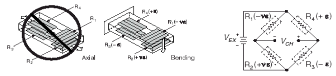
Full bridge circuit

- Type I – (only for bend) doubled in each sense of deformation – increasing sensitivity



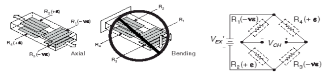
$$strain\ (\varepsilon) = \frac{-V_r}{GF}$$

- Type II – (only for bend) 2 active a 2 passive strain gage (compensation of Poisson's effect and



$$strain\ (\varepsilon) = \frac{-2V_r}{GF(1+\nu)}$$

- Type III – the alternative of type II for axial deformation



$$strain\ (\varepsilon) = \frac{-2V_r}{GF[(\nu+1)-V_r(\nu-1)]}$$

Strain gage application overview

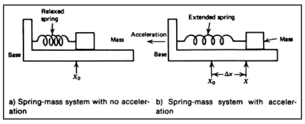
Measurement Type	Quarter Bridge		Half-Bridge		Full-Bridge		
	Type I	Type II	Type I	Type II	Type I	Type II	Type III
Axial Strain	Yes	Yes	Yes	No	No	No	Yes
Bending Strain	Yes	Yes	Yes	Yes	Yes	Yes	No
Compensation							
Transverse Sensitivity	No	No	Yes	No	No	Yes	Yes
Temperature	No	Yes	Yes	Yes	Yes	Yes	Yes
Sensitivity							
Sensitivity at 1000 $\mu\varepsilon$	~0.5 mV/V	~0.5 mV/V	~0.65 mV/V	~1.0 mV/V	~2.0 mV/V	~1.3 mV/V	~1.3 mV/V
Installation							
Number of Bonded Gages	1	1*	2	2	4	4	4
Mounting Location	Single Side	Single Side	Single Side	Opposite Sides	Opposite Sides	Opposite Sides	Opposite Sides
Number of Wires	2 or 3	3	3	3	4	4	4
Bridge Completion Resistors	3	2	2	2	0	0	0

*A second strain gage is placed in close thermal contact with structure but is not bonded.

ACCELEROMETERS

Acceleration

- Acceleration is the measure of the change in velocity of an object with respect to time: a=dv/dt
- Newton's law *F=ma*
- Hook's law(spružina) $F = k\Delta x$
- $ma = k\Delta x$ $$a = \frac{k}{m}\Delta x$$

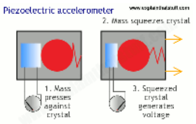


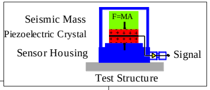
a) Spring-mass system with no acceleration
b) Spring-mass system with acceleration

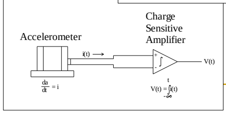
- Standard SI unit – meters per second per second or meters per second squared
- Often in g (earth gravity = 9,81m/s^2) (1 – 100)
- Frequency band from DC up to tens kHz
- Very common in industry, components of machins, seismic measurements, … - tablet, cellular phone.

Principles I

- 1D or 3D (tri-axial) accelerometers
- Isolated or grounded
- Passive piezoelectric
  - Available in compression and shear modes

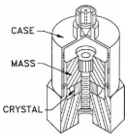






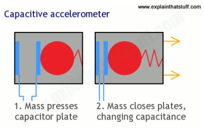
$\frac{da}{dt} = i$

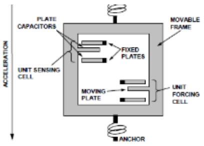
$V(t) = \int_{-\infty}^{t} i(t)$



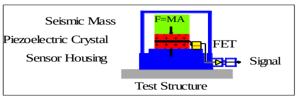
Principle 2

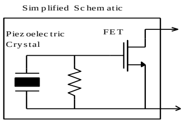
- Capacitive ussualy in the form of micro electro mechanical systems (MEMS) in the form of integrated circuits (www.analog.com)



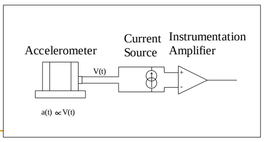


Active Accelerometers





- Front end circuitry supplied inside sensor
- Energized with a constant current source
- Sensing
  - DC current
  - Instrumentation amplifier



$a(t) \propto V(t)$

Passive Versus Active

Passive

Advantages

- Variable signal range
- Temperatures up to 500°C

Disadvantages

- Sensitive to noise
- External conditioning required

Applications:

Extreme temperatures
Varying sensitivities

Active

Advantages

- Noise immunity
- Built-in signal conditioning

Disadvantages

- Fixed signal range
- Limited temperature range 120°C

Applications:

Noisy environments
Simpler systems

Accelerometer Errors

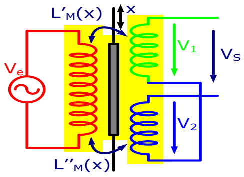
- Drift (DC systems)
- Low frequency roll-off (AC systems)
- Accelerometer non-linearities
- Current Source non-linearities (active sensors)
- External noise sources
- Ground loops

MEASUREMENT OF POSITION AND SIMILAR QAUNTITIES

LVDT

- Linear Voltage Differential Transformer
- Linear Variable Differential Transformer
- Primary application: measurement of position or movement

LVDT principle



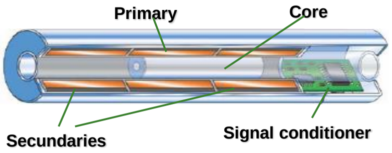
3 coils

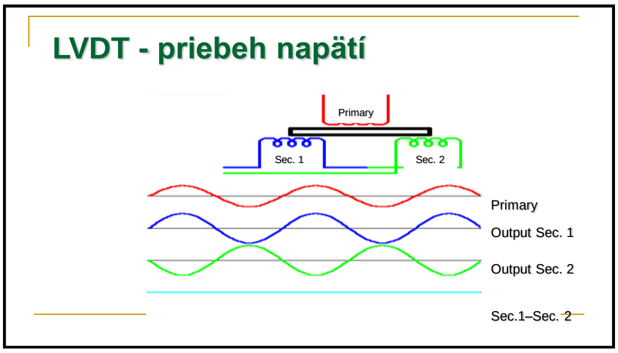
1 primary and 2 secondaries

Two secondaries symmetrically positioned in relation to the primary

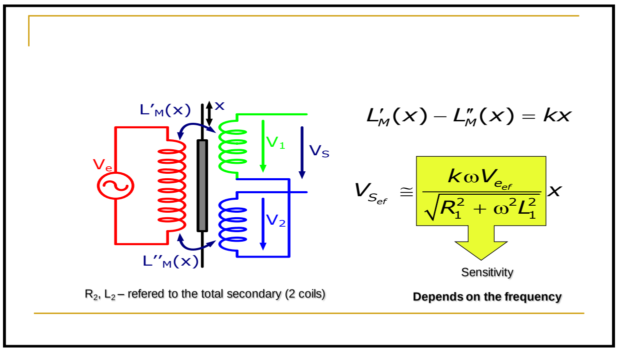
They are mounted along a single axis with a ferromagnetic core that can be displaced along that direction.

LVDT example





LVDT - priebeh napätí



$$L'_M(x) - L''_M(x) = kx$$

$$V_{S_{ef}} \cong \boxed{\frac{k\omega V_{e_{ef}}}{\sqrt{R_1^2 + \omega^2 L_1^2}}}\, x$$

Sensitivity

R_2, L_2 – refered to the total secondary (2 coils)

Depends on the frequency

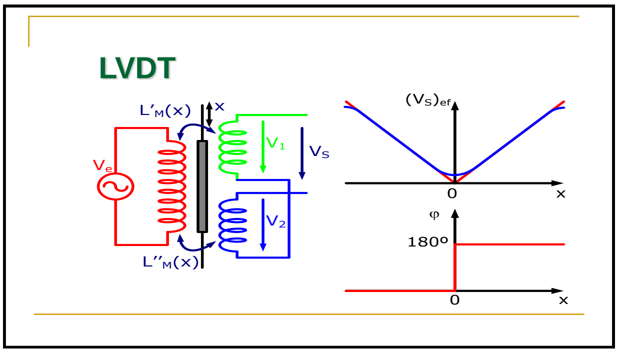
LVDT

The sensitivity has a maximum for

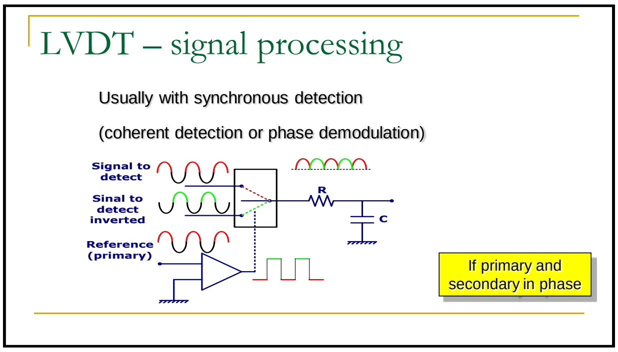
$$f = \frac{1}{2\pi}\sqrt{\frac{R_1 R_2}{2L_1 L_2}}$$

At this frequency the input (primary) and the output (secondary) voltages are in phase or in opposition.

This is important for the synchronous detection.



LVDT

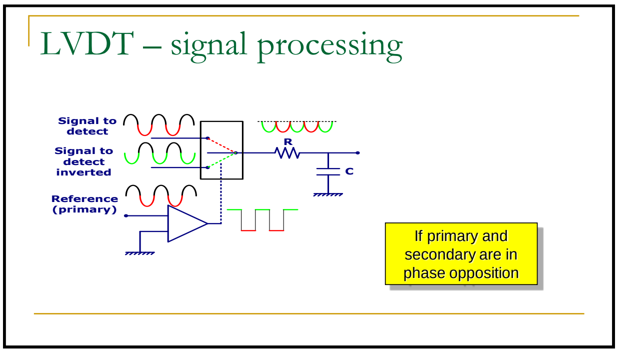


LVDT – signal processing

Usually with synchronous detection

(coherent detection or phase demodulation)

If primary and secondary in phase



LVDT – signal processing

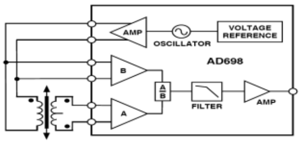
If primary and secondary are in phase opposition

LVDT – signal processing example

Integrated signal conditioner (AD698)

FEATURES
Single Chip Solution, Contains Internal Oscillator and Voltage Reference
No Adjustments Required
Interfaces to Half-Bridge, 4-Wire LVDT
DC Output Proportional to Position
20 Hz to 20 kHz Frequency Range
Unipolar or Bipolar Output
Will Also Decode AC Bridge Signals
Outstanding Performance
  Linearity: 0.05%
  Output Voltage: ±11 V
  Gain Drift: 20 ppm/°C (typ)
  Offset Drift: 5 ppm/°C (typ)

FUNCTIONAL BLOCK DIAGRAM

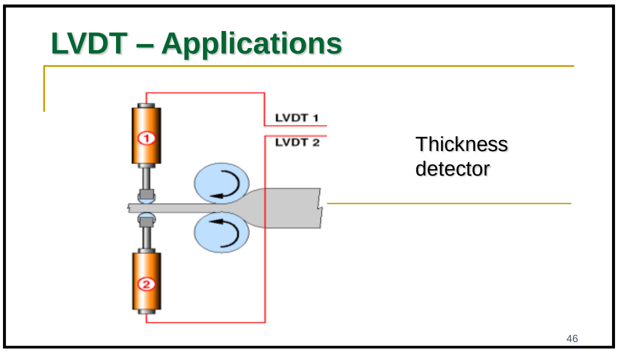


LVDT properties

- High resolution: better than 0,1%
- It works with very low friction (no contact between the core and the coils)
- High mechanic lifetime
- Resistant to “over-displacements”
- Sensitivity on one direction
- High sensitivity (depends on the frequency)
- Reproducibility
- High dynamic response
- High linearity (0,05%)

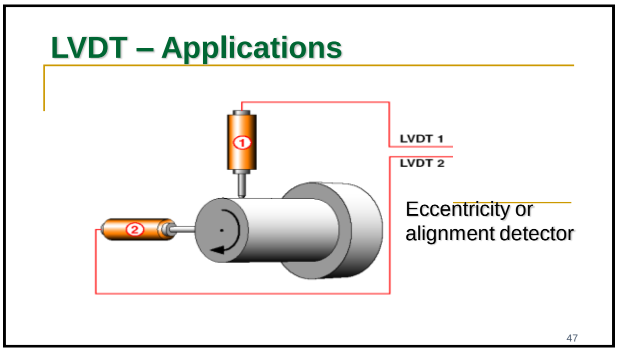
LVDT examples of applications

- Measurement of displacement and position
- In zero-detectors, used in position feedback systems (aircrafts and submarines)
- In machine-tools, as positioning detectors



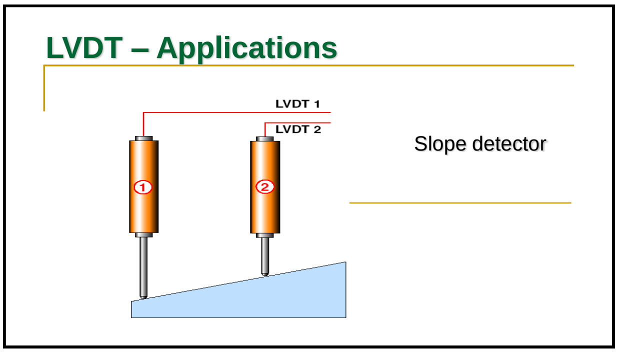
LVDT – Applications

Thickness detector



LVDT – Applications

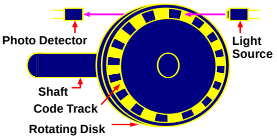
Eccentricity or alignment detector



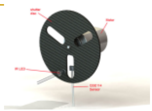
LVDT – Applications

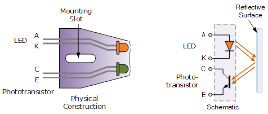
Slope detector

Optical Encoder



Light sensing
- Transmission
- Reflection

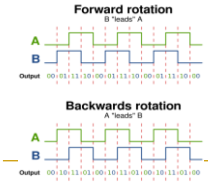


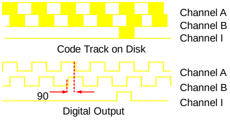


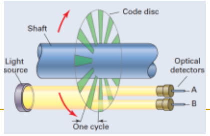
Alternatively magnetic system with Hall probe can be used

Quadrature (or Incremental) Encoder

Two detectors with a little different position
Sense of rotation can be detected

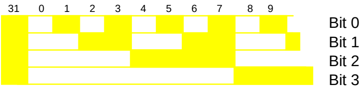




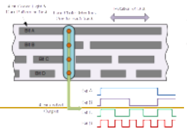


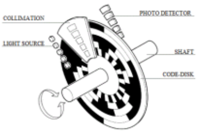
Absolute Encoder

Position detection (rotary)
Remember position also after reset of electronics
Coding: Gray code



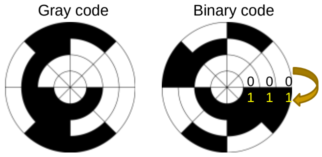
Code Track on Disk





Absolute Encoder

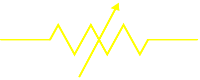
- Gray code (binary code can results in wrong output data)
  - Adjacent codes differ always only in one bit

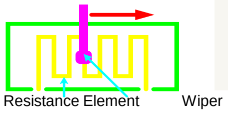


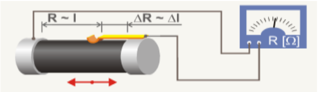
Example: 3 bits at once
000 – correct data
010
011 error
111 – correct data

Potentiometers

- Potentiometers – variable voltage dividers
- Wire wound or conductive plastic







Potentiometers

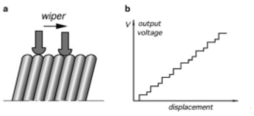
Servo Mount

Bushing Mount

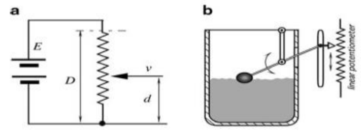
Linear Pots

String Pots

Resistance coil – stepwise output

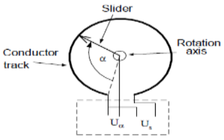


Potentiometer examples



Moving of wiper change output voltage – voltage is lineary proporcional to the position, e.g., liquid level

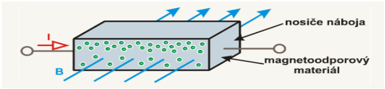
Potentiometer example



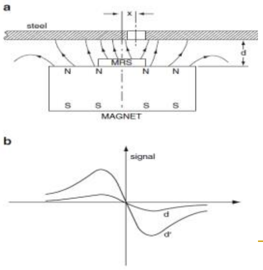
Throttle valve of engine

1.3 Magnetoresistor

- Resistive component sensitive on magnetic field

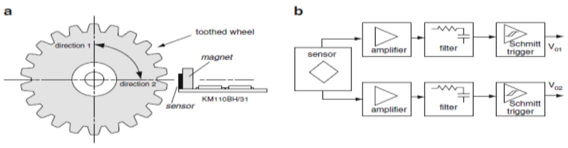


Position sensing

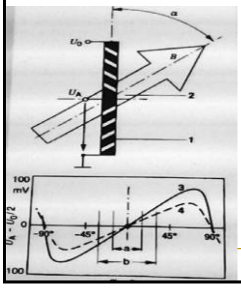


Position of small aperture modifies magnetic field, what results in changing resistance of magnetoresistor.

Sensing rotation



Angle position sensing



Magnetoresistor – its resistance depends not only on magnetic field magnitude but also on magnetic vector orientation.

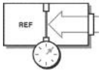
Magnetic field vector orientation can be detected using two perpendicular magnetoresistors

PRESSURE MEASUREMENT

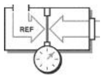
What is presure

- http://www.ni.com/white-paper/13034/en/
- Pressure is defined as force per unit area that a fluid exerts on its surroundings. Pressure, P, is a function of force, F, and area, A: P = F/A
- Existujú 3 princípy merania

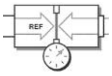
Absolute



GaugePresure

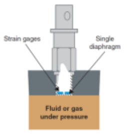


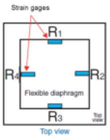
Differential Presure

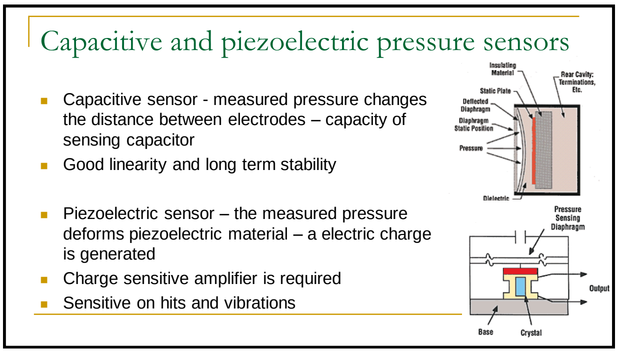


Strain gage bridge-based principle

- Change of pressure causes the diaphragm to deflect.
- The deflection is sensed by strain gages connected in a bridge (see the cahper on strain gages)







Capacitive and piezoelectric pressure sensors

- Capacitive sensor - measured pressure changes the distance between electrodes – capacity of sensing capacitor
- Good linearity and long term stability

- Piezoelectric sensor – the measured pressure deforms piezoelectric material – a electric charge is generated
- Charge sensitive amplifier is required
- Sensitive on hits and vibrations