

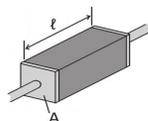
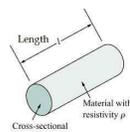
MEMS Inteligentné senzory a aktuátory

Ing. Richard Balogh

2. Odporové snímače



Elektrický odpor



$$R = \rho \frac{l}{A}$$



Závislosť od

1. geometrické rozmery
2. teploty

$$R = R_0(1 + \alpha \Delta t)$$

kovy: PTC

polovodiče a oxidy: NTC

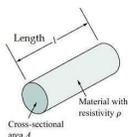
ale aj

$$l = l_0(1 + \gamma \Delta t)$$

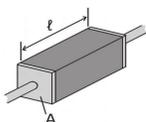
3. piezorezistívny jav
4. vlhkosť

Elektrický odpor

2.1 Závislosť na rozmeroch a deformácii

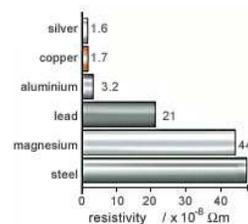


$$R = \rho \frac{l}{A}$$



Elektrický odpor - tabuľky

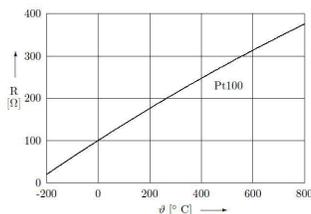
- ◆ Strain Gages: 120Ω, 350Ω, 3500Ω
- ◆ Weigh-Scale Load Cells: 350Ω - 3500Ω
- ◆ Pressure Sensors: 350Ω - 3500Ω
- ◆ Relative Humidity: 100kΩ - 10MΩ
- ◆ Resistance Temperature Devices (RTDs): 100Ω, 1000Ω
- ◆ Thermistors: 100Ω - 10MΩ



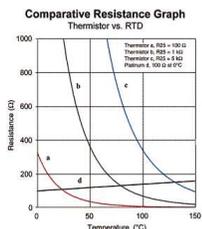
Elektrický odpor

2.2 Závislosť od teploty

$$R(\vartheta) = R_0(1 + A\vartheta + \beta\vartheta^2) \quad A = 3,9083 \cdot 10^{-3} \quad B = -5,775 \cdot 10^{-7}$$

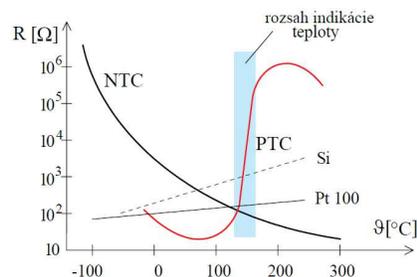


Obr. 33: Prevodová charakteristika Pt100.



Elektrický odpor

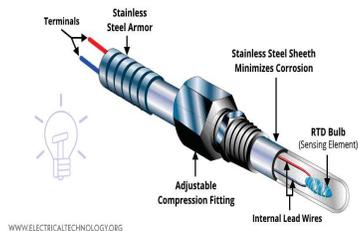
Závislosť od teploty



2. Resistive sensors

2.2 Odporové snímače teploty

RTD - Resistance Temperature Detector Construction, Types, Working & Applications



WWW.ELECTRICALTECHNOLOGY.ORG



2. Resistive sensors

Odporové snímače teploty

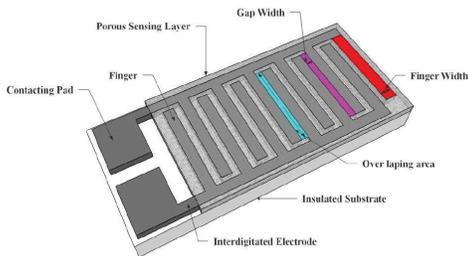


Automotive



Industrial

Elektrický odpor Závislost' od vlhkosti



Elektrický odpor Závislost' od deformácie

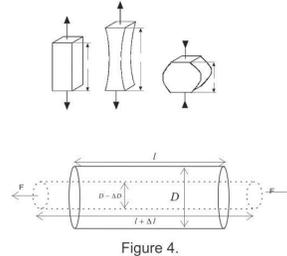


Figure 4.

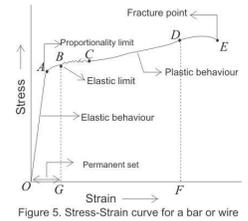


Figure 5. Stress-Strain curve for a bar or wire

Elektrický odpor

Gage factors and the piezoresistive effect

What is the relation between deformation and resistance?

Gage factor: $F = \frac{\Delta R/R}{\epsilon_L}$

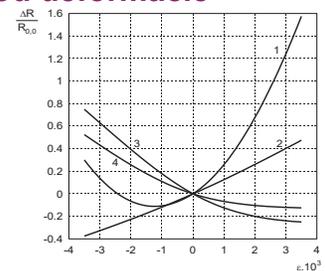
$$\Delta R = \frac{\partial R}{\partial \rho} \Delta \rho + \frac{\partial R}{\partial L} \Delta L + \frac{\partial R}{\partial A} \Delta A + \text{higher order terms}$$

$$\frac{\Delta R}{R} = \frac{\Delta \rho}{\rho} + \frac{\Delta L}{L} - \frac{\Delta A}{A}$$

Metals	Semiconductors
Changes in geometry dominate	Changes in resistivity dominate
$\frac{\Delta R}{R} = \frac{\Delta L}{L} - \frac{\Delta A}{A}$	$\frac{\Delta R}{R} = \frac{\Delta \rho}{\rho}$

** Strain causes differences in atomic spacing, which in turn causes changes in band gaps and thus ρ .*

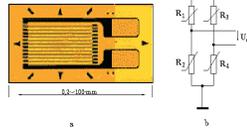
Elektrický odpor 2.4 Závislost' od deformácie



Závislosť relatívnej zmeny odporu od relatívnej deformácie pre kremík:
 (1) P-typ s $\rho > 10^3 \Omega \cdot \text{m}$ (3) N-typ s $\rho > 10^3 \Omega \cdot \text{m}$
 (2) P-typ s $\rho = 2 \cdot 10^4 \Omega \cdot \text{m}$ (4) N-typ s $\rho = 3,1 \cdot 10^4 \Omega \cdot \text{m}$

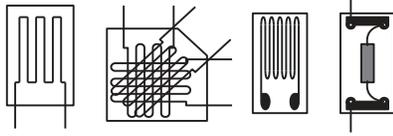
Tenzometer

Strain Gauge



Def.:
pomerné predĺženie (strain) ϵ

$$\epsilon = \frac{\Delta L}{L}$$



Tenzometre

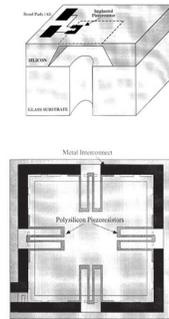
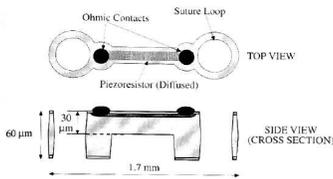
Tab.1 Prehľad vlastností nalepených tenzometrov

Tenzometre	Fóliové	Polovodičový	
Typ	KFC-2-D1-23 (R_{10})	KFC-5-350-C1-23 (R_{10} , R_{11} , R_{12})	KSP-2-E3 (R_{10})
Odpor R [Ω]	119.9±0.4	350±0.6	110±2%
Súčiniteľ deformácie citlivosti K	2.11	2.1±1%	124±3%
Teplotný súčiniteľ deformácie citlivosti α_{ϵ} [1/°C]	≈ 0	≈ 0	0.14%
Teplotný súčiniteľ elektrického odporu $\alpha_{R_{10}}$ [$\mu\Omega/m/°C$, tj. $e/°C$]	1.8	1.8	13.8
Súčiniteľ teplotnej rozťažnosti materiálu tenzometra α_L [$\mu m/m/°C$]	≈ 0	≈ 0	7±22
Výrobca	Kyowa Tokyo	Kyowa Tokyo	Kyowa Tokyo
Max. relatívne predĺženie ϵ [$\mu m/m$]	±3000	±3000	±2000
Dĺžka aktívnej mriežky [mm]	2	5	2
Poznámka	tepelná kompenzácia pre namáhaný materiál-hliník (23 $\mu m/m/°C$)	tepelná kompenzácia pre namáhaný materiál-hliník (23 $\mu m/m/°C$)	

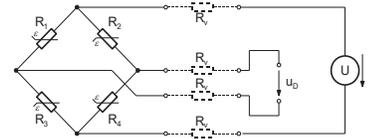
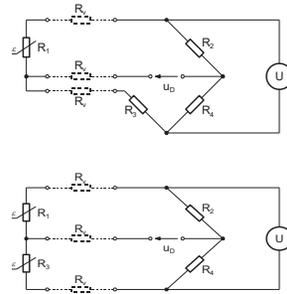
MEMS Tenzometre

Membrane type gauges: typical pressure sensor

Implantable strain gauge



Tenzometre



Využitie tenzometrov

Sila

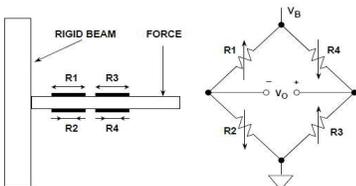


Figure 3.83: A beam force sensor using a strain gage bridge

Využitie tenzometrov

Váženie



2. Resistive sensors

2.2 Potenciometrické snímače polohy

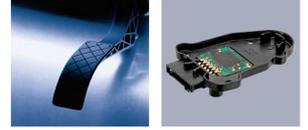
- Odporové (potenciometrické) snímače so spojitým výstupným signálom patria do skupiny **pasívnych meracích prvkov** a sú vhodné na priame meranie, napr. **polohy prvku** mechanickej zostavy alebo **na meranie neelektrických veličín**, ktoré sa dajú transformovať na zmenu polohy, čiže na posunutie



Konstruktívne riešenia odporových snímačov polohy s kruhovou dráhou

- potenciometer s jedným odporovým vodičom
- stupňovitá odporová dráha
- odporový vodič navinutý na nosnej podložke
- odporová dráha tvorená elektrolytom

Príklady automotive



Electronic Pedal Sensor

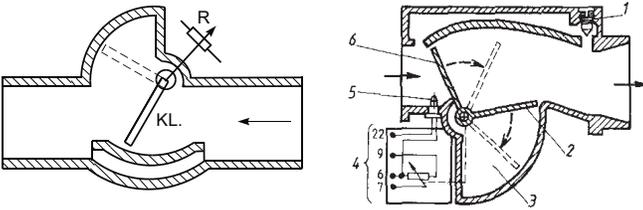


E-GasThrottling Device



Gear Selection Sensor

Príklad potenciometrického snímača polohy v automobile



Klapkový snímač množstva nasávaného vzduchu
 $Q = f(\Delta p, \text{polohy klapky})$
 Poloha plynového pedálu

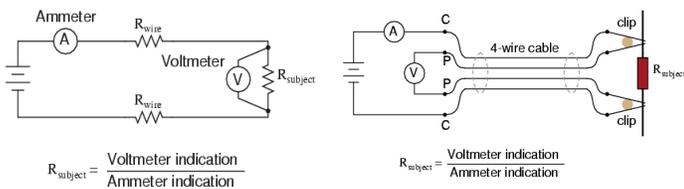
Meranie odporu

- meranie U a I
- meranie U (konšt. I)
- prevod na frekvenciu
- mostíkové zapojenia



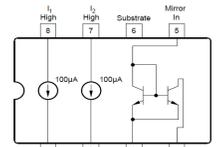
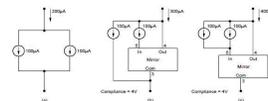
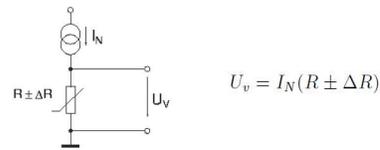
Meranie odporu

Meranie napätia a prúdu



Meranie odporu

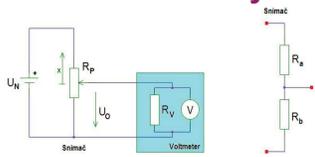
Meranie napätia / zdroj prúdu



REF200
 -- 2x 100µA current sources
 -- 1x current mirror

Meranie odporu

Potenciometrický snímač polohy

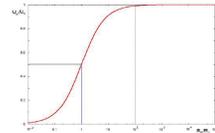


Obr. 1. Lineárny potenciometrický snímač.

$$R_b = R_p \cdot x$$

$$R_a = R_p(1 - x)$$

$$U_0 = U_N \frac{R_b}{R_a + R_b} = U_N \frac{R_p x}{R_p} = U_N \cdot x$$



Obr. 2. Impedančné prispôbenie snímača.

Schémy zapojenia potenciometrických snímačov polohy



Pre nezaťažený potenciometer platí $U_2 = k \cdot x$, resp. $U_2 = k \cdot \alpha$

príčom konštanta úmernosti k je určená pomerom $k = \frac{U_{2max}}{x_{max}} = \frac{U_{2max}}{\alpha_{max}}$

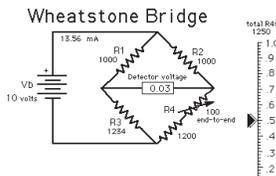
Podmienky:

- stabilné a konštantné napájanie
- prúd nesmie senzor ohrievať
- následný obvod impedančne prispôbený

Mostíkové zapojenia

Wheatstonov mostík

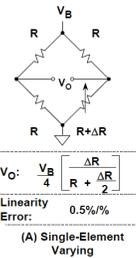
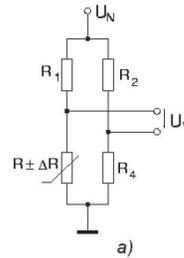
The Differential Resistance Measurer



Samuel Hunter Christie

Meranie odporu

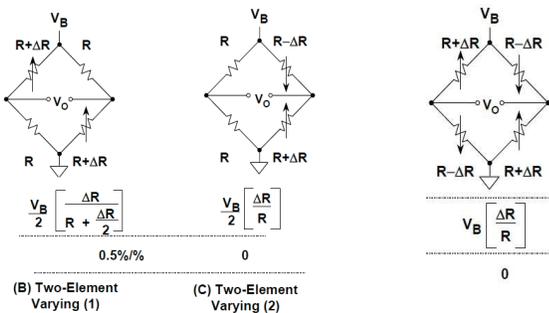
Mostíkové zapojenia



$$U_v = U_N \left(\frac{R \pm \Delta R}{2R \pm \Delta R} - \frac{1}{2} \right)$$

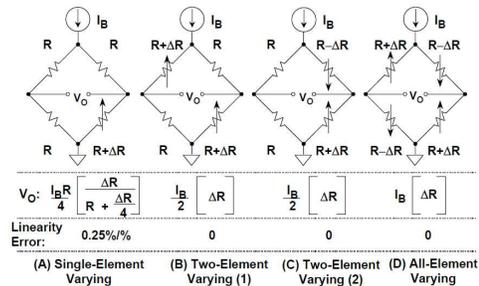
Meranie odporu

Mostíkové zapojenia



Meranie odporu

Mostíkové zapojenia



Meranie odporu
Mostíkové zapojenia - vyhodnotenie

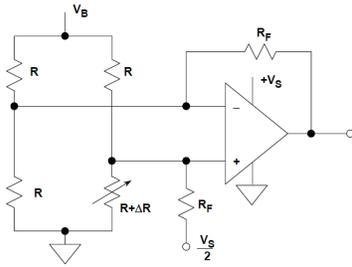


Figure 4-9: Using a single op amp as a bridge amplifier

Meranie odporu
Mostíkové zapojenia - vyhodnotenie

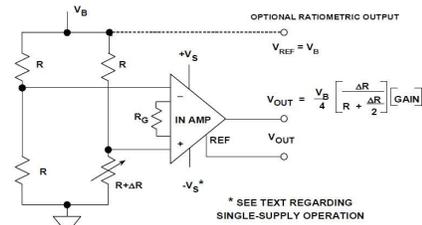
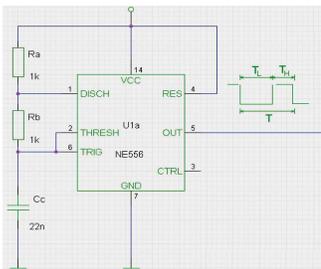


Figure 4-10: A generally preferred method of bridge amplification employs an instrumentation amplifier for stable gain and high CMR

Meranie odporu
Prevod na frekvenciu



$$f = \frac{1,429}{C_c(R_a + 2R_b)}$$

$$T_H = 0,7(R_a + R_b)C_c$$

$$T_L = 0,7R_bC_c$$

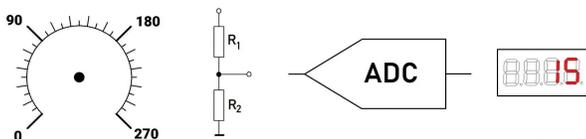
Zaťažovacia konštanta

Zaťažovacia konštanta D [$W \cdot K^{-1}$] predstavuje príkon P , potrebný k ohriatiu senzora o teplotu $\Delta \vartheta = 1K$ nad teplotu okolitého prostredia.

Max. hodnota meracieho prúdu

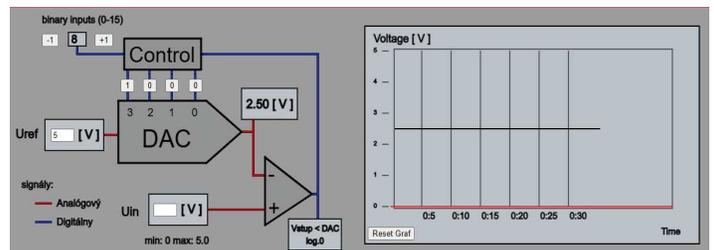
$$I_{dov} = \sqrt{\frac{\Delta \vartheta_{max} D}{R}} \quad [W \cdot K^{-1}]$$

Príklad 1: meranie

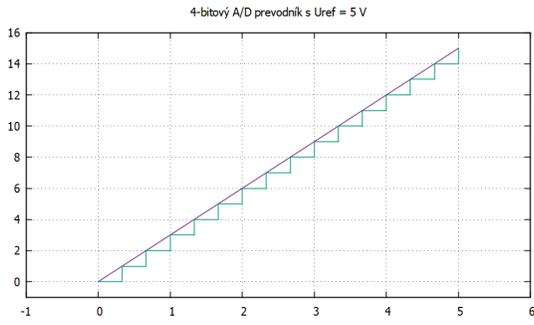


Uhol	N
[°]	[-]
0	0
90	5
180	10
270	15

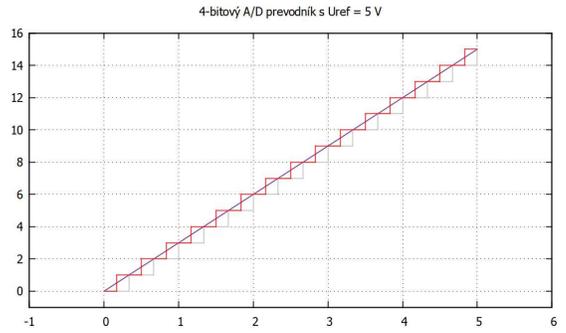
Príklad 1: 4-bitový A/D prevodník



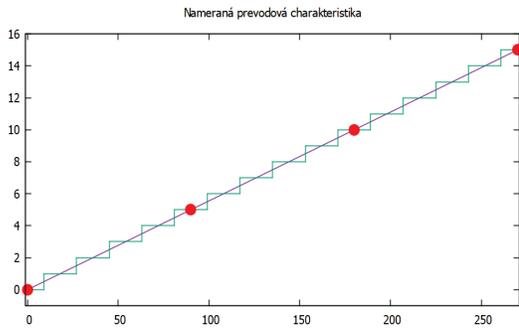
Príklad 1: 4-bitový A/D prevodník



Príklad 1: 4-bitový A/D prevodník



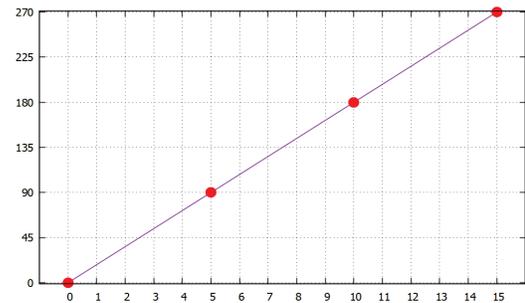
Príklad 1: charakteristika



Uhol	N
[°]	[-]
0	0
90	5
180	10
270	15

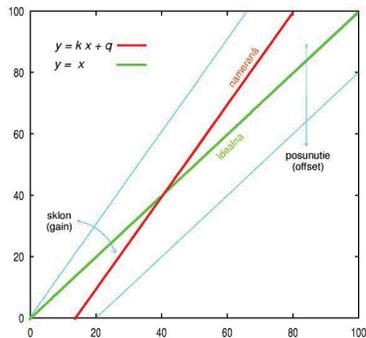
Príklad 1: inverzná char.

```
int N = analogRead(vstup4);
Uhol = f(N);
```



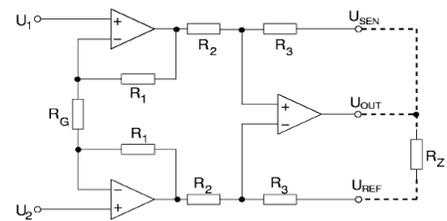
N	Uhol
[-]	[°]
0	0
5	90
10	180
15	270

Nastavovanie K a q



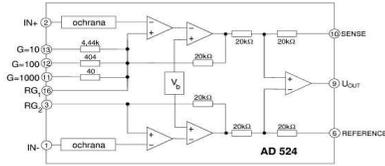
Klasický prístrojový zosilňovač

$$U_v = K(u_1 - u_2) = K u_1 - K u_2$$



Integrovaný obvod AD 524

Analog Devices, TESLA (MAC524), a pod.

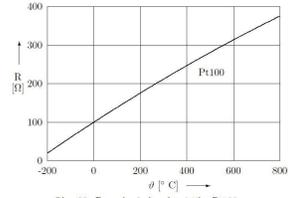


Nelinearita	0,003%	Zosilnenie	1, 10, 100, 1000, A
CMRR	120 dB	Offset	50 μV
Drift	0,5 μV/°C	Šum	0,3 μV p-p
I vst	50 nA	R vst	10 ⁹ Ω

Ochrana vstupov (max. 3 mA pre ±36 V). Puzdro DIL 16

Prevodová charakteristika

Transfer function (I/O characteristics)



Obr. 33: Prevodová charakteristika Pt100.

θ [°C]	-5	0	5	10	15	20	25	30	35	40	45
R [Ω]	98,04	100,000	101,953	103,903	105,849	107,793	109,735	111,673	113,608	115,541	117,470
θ [°C]	50	55	60	65	70	75	80	85	90	95	100
R [Ω]	119,397	121,321	123,242	125,160	127,075	128,987	130,897	132,803	134,707	136,608	138,505

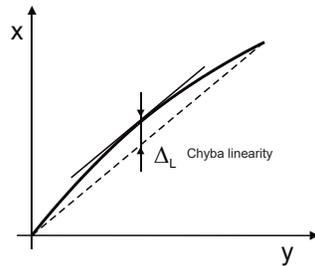
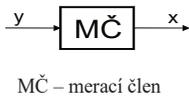
Tabuľka 3: Hodnoty odporu pre snímač Pt 100 (IEC 751).

Závislosť odporu Pt 100 na teplote nie je lineárna a dá sa v rozsahu 0 – 850 °C popísať polynómom

$$R(\theta) = R_0(1 + A \cdot \theta + B \cdot \theta^2)$$

kde R_0 je odpor pri teplote 0 °C (t.j. 100 Ω), A a B sú materiálové konštanty: $A = 3,9083 \cdot 10^{-3} \text{ } ^\circ\text{C}^{-1}$; $B = -5,775 \cdot 10^{-7} \text{ } ^\circ\text{C}^{-2}$ (podľa IEC 751).

Nelineárna prevodová charakteristika



Inverzná prevodová charakteristika

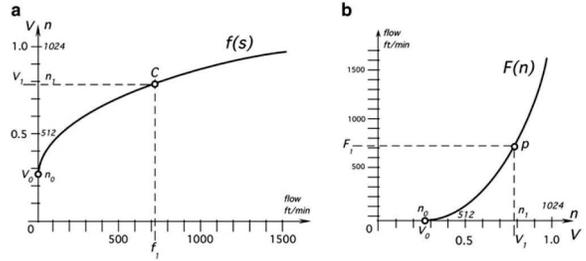
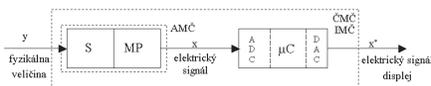
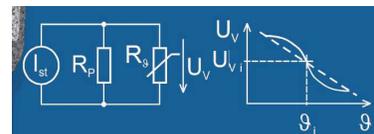


Fig. 2.1 Transfer function (a) and inverse transfer function (b) of a thermo-anemometer

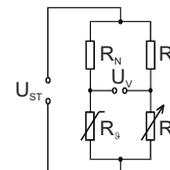
Linearizácia prevodovej charakteristiky snímača



Linearizácia paralelným zapojením



Linearizácia sériovo-paralelným zapojením



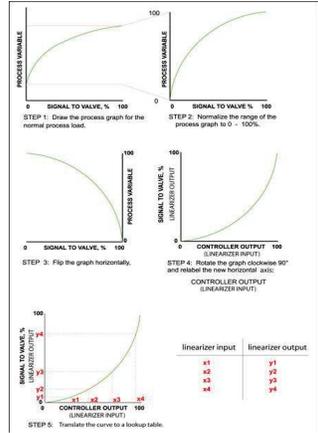
Linearizácia tabuľkou

Uhol	N
[°]	[-]
0	0
90	5
180	10
270	15

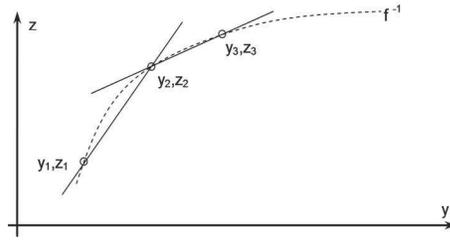


N	Uhol
[-]	[°]
0	0
7	90
12	180
15	270

```
#include <avr/pgmspace.h>
const PROGMEM int table[] = {11,12,15,...};
```

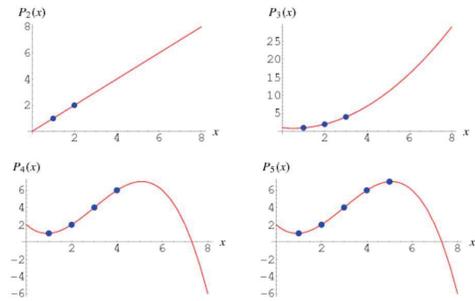
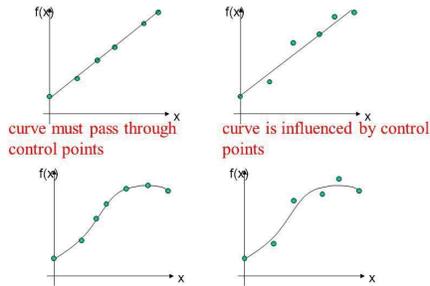


Linearizácia po častiach



```
if (adcValue > y1) && (adcValue <= y2)
z = k2 * adcValue + q2;
return(y)
```

Interpolation vs approximation

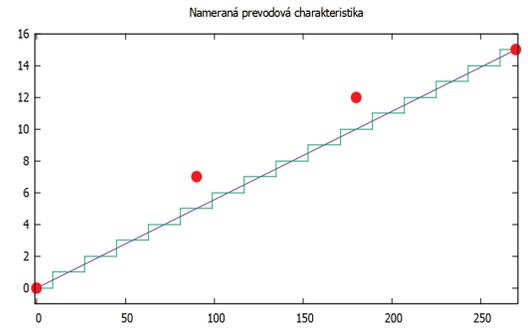


The Lagrange interpolating polynomial is the polynomial $P(x)$ of degree $\leq (n - 1)$ that passes through the n points $(x_1, y_1 = f(x_1)), (x_2, y_2 = f(x_2)), \dots, (x_n, y_n = f(x_n))$, and is given by

$$P(x) = \sum_{j=1}^n P_j(x),$$

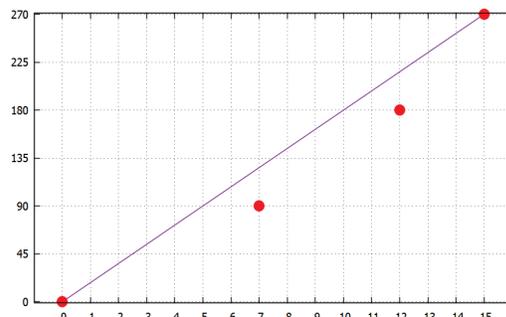
Príklad 2: charakteristika namerané údaje

Uhol	Lin	N
[°]	[-]	[-]
0	0	0
90	5	7
180	10	12
270	15	15



Príklad 2: inverzná char.

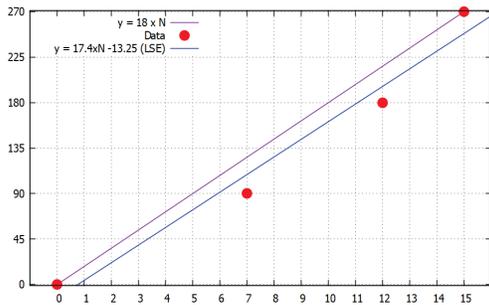
Uhol	Lin	N
[°]	[-]	[-]
0	0	0
90	5	7
180	10	12
270	15	15



```
> N = [0 15]
> Uhol = [0 270]
> p = polyfit(N,Uhol,1)
p =
??? ???
> polyval(p,[0 7 12 15])
0 126 216 270
t.j.: 00 +36 +36 00
```

Príklad 2: inverzná char. metóda najmenších štvorcov least squares estimation

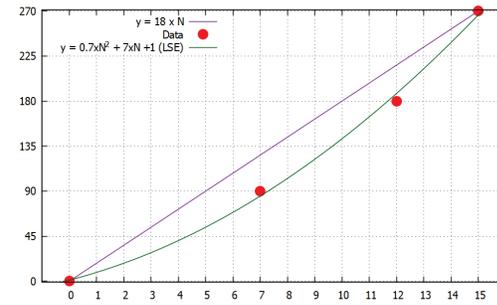
Uhol	Lin	N
[°]	[-]	[-]
0	0	0
90	5	7
180	10	12
270	15	15



```
> N = [0 7 12 15]
> Uhol = [0 90 180 270]
> p = polyfit(N,Uhol,1)
p =
    17.4419    -13.2558
> polyval(p,N) - Uhol
-13.2558  18.8372  16.0465  -21.6279
```

Príklad 2: inverzná char. metóda najmenších štvorcov least squares estimation

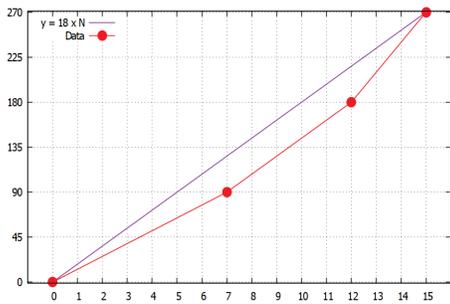
Uhol	Lin	N
[°]	[-]	[-]
0	0	0
90	5	7
180	10	12
270	15	15



```
> N = [0 7 12 15]
> Uhol = [0 90 180 270]
> p = polyfit(N,Uhol,2)
p =
    0.7091    7.0364    1.0909
> polyval(p,N) - Uhol
    1.09  -4.98  7.63  -3.81
```

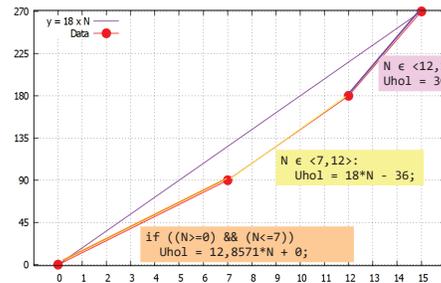
Príklad 2: inverzná char. po častiach lineárna náhrada PWL - piecewise linear approx.

Uhol	Lin	N
[°]	[-]	[-]
0	0	0
90	5	7
180	10	12
270	15	15



Príklad 2: inverzná char. po častiach lineárna náhrada PWL - piecewise linear approx.

Uhol	Lin	N
[°]	[-]	[-]
0	0	0
90	5	7
180	10	12
270	15	15



Príklad 2: inverzná char. tabuľka

N	Uhol
[-]	[°]
0	0
1	13
2	26
3	38
4	51
5	64
6	77
7	90
8	108
9	126
10	144
11	162
12	180
13	210
14	240
15	270

Uhol	Lin	N
[°]	[-]	[-]
0	0	0
90	5	7
180	10	12
270	15	15

```
> N = [0 7]
> Uhol = [0 90]
> p = polyfit(N,Uhol,1)
p =
    12.8571     0
> polyval(p,[0 1 2 3 4 5 6 7])
    0    12.8571    25.7143    38.5714
    51.4286    64.2857    77.1429    90.0000

> N = [7 12]
> Uhol = [90 180]
> p = polyfit(N,Uhol,1)
> polyval(p,[7 8 9 10 11 12])

> N = [12 15]
> Uhol = [180 270]
> p = polyfit(N,Uhol,1)
> polyval(p,[12 13 14 15])
```

Príklad 2: inverzná char. tabuľka

Uhol	Lin	N
[°]	[-]	[-]
0	0	0
90	5	7
180	10	12
270	15	15

N	Uhol
[-]	[°]
0	0
1	13
2	26
3	38
4	51
5	64
6	77
7	90
8	108
9	126
10	144
11	162
12	180
13	210
14	240
15	270

```
#include <avr/pgmspace.h>

//          0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15
const PROGMEM int table[] = {0,13,26,38,51,64,77,90,108,126,144,162,180,210,240,270};

...

int N = analogRead(vstup4);
Uhol = table[N];
```

Spotreba pamäti:
sizeof(int) = 2; ==> 2x16 B = 32 B
Pre 10-bitový prevodník:
2 x 1024 = 2kB