Exam - PoMS, 23/01/2014

- Write each question on a sheet of paper.
- Write your **name** and **student ID** on each sheet.
- Pay attention to units. A numerical result without a unit will be considered wrong!
- Only a regular calculator is allowed.
- This is NOT an open book exam.
- You are allowed to bring one A4 page with your own notes (one side only).
- You have **3 hours** to complete the exam.
- Note: $\mathscr{L}(t^n\, e^{-\alpha t}) = \frac{n!}{(s+\alpha)^{n+1}}$.

Question 1: General (2 points)

a) What is a *Schmitt trigger* and what is its application? Describe briefly its working principle.

b) Explain the working principle behind a *thermocouple.*

c) The *autocorrelation function* is often used to detect the presence of a period signal buried in random noise. Explain qualitatively what the autocorrelation function embeds and how it can be used to identify the presence of a buried signal.

d) Describe the working principle of a *tachogenerator* in connection to the concept of *reluctance.*

Question 2: A pressure gauge (2 points)

The table below characterises a pressure gauge designed for operation at room temperature (25 °C, standard condition).

Pressure (bar)	1	2	3	4	5	6
I_{out} [mA] (25 °C)	3.9	7.0	10.1	13.2	16.3	19.4
I_{out} [mA] (35 °C)	3.5	7.2	10.9	14.6	18.3	22.0

a) Explain whether the environment variable is modifying, interfering, or both modifying and interfering.

b) Determine the values of K_M, K_I, a, and K associated with the generalized model equation $O = (K + K_M \cdot I_M) \cdot I + a + K_I \cdot I_I$. Note down the units of the parameters!

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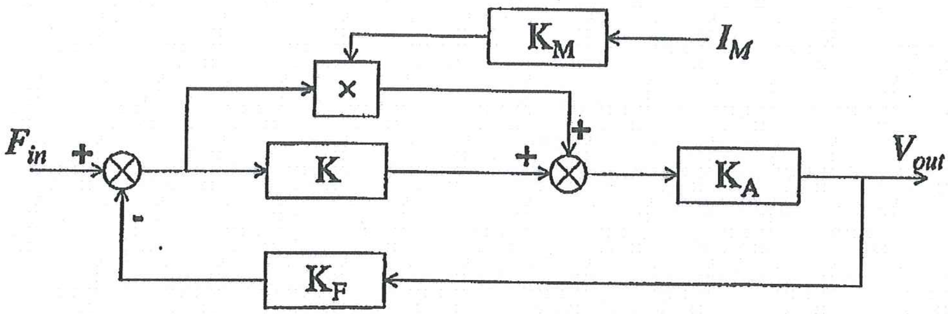

Figure 1: A high-gain negative feedback system.

Question 3: A negative feedback system (2 points)

Figure 1 shows the block diagram of a force transducer (force F_{in} to voltage V_{out}) with a high-gain negative feedback. A sensing element has a sensitivity of K, followed by an amplifier with a high gain K_A, and a feedback element with a sensitivity K_F. The sensing element is influenced by a modifying interference, I_M, with a sensitivity of K_M.

a) Derive the exact equation that describes the static behavior of the system.

b) The high-gain negative feedback system is designed such that the amplifier gain, K_A, is "large". Give an expression that quantifies the meaning of "large", such that $V_{out} \approx F_{in}/K_F$.

c) What is/are the advantage(s) of this technique of "high-gain negative feedback"?

Question 4: A temperature measurement system (2 points)

A temperature measurement system consists of a thermocouple, an amplifier, and a recorder. The thermocouple can be represented by a 1^{st}-order low-pass system with a time constant $\tau = 10$ s and a steady-state sensitivity of 10^{-4} V/°C. The amplifier has a multiplication factor of 10^3 and can be considered as a purely static system. The dynamic response of the *total* measurement system was found to be $G(s) = 1/(1 + 12s + 20s^2)$, where $G(s)$ is the transfer function with s as the Laplace variable (with units $\sec^{-1}$). Note that the steady-state sensitivity of the complete system is unity.

a) Give an expression for the transfer function of the recorder and its steady-state sensitivity.

b) The true temperature changes suddenly by 10 °C from a steady-state condition. Find an expression of the change of the temperature given by the recorder.

c) Estimate the bandwidth of the total measurement system and motivate your answer.

Question 5: Two-element resistance sensor bridge (2+1 points)

Consider a two-element resistance sensor bridge as indicated in Fig. 2. The bridge consists of two identical metal resistance sensors. One sensor is placed at a temperature T_1 (in °C) and the other placed at a fixed reference temperature T_2=0 °C. The formula for resistance as a function of temperature is given in the figure with the temperature coefficient $\alpha=5\times10^{-3}$ °C^{-1} and R_0=100 Ω. The sensor indicated with T_1 operates in a range between 0 and 50 °C.

a) What is the choice for R_3/R_4 such that E_{Th}=0 when T_1=T_2 (balanced bridge). Motivate your answer.

b) Take R_3=R_4=R_0=100 Ω. The system is calibrated by varying the supply voltage V_S such that E_{Th}=1 V at T_1=50 °C. What value of V_S is required and how large is the non-linearity at T_1=25 °C?

c) What choice for R_3 and R_4 is needed to improve significantly the linearity of the system and to obtain the relation

$$E_{Th} = V_S\left(\frac{R_0}{R_3}\right)\alpha T_1.$$

What price one pays for achieving linearity? Motivate your answers.

d) Take V_S=12 V and R_3=R_4=10 kΩ. How large is the maximum power dissipation through sensor R_1?

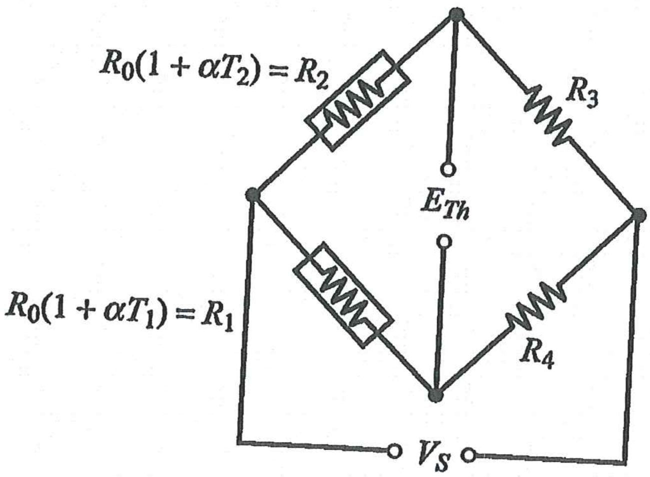

Figure 2: A two-element resistance sensor bridge.

PUMS exam 23/01/2014 Antwoord (model)

eenheid: 0,25 punt, maximum score 10, max. punt 11 (1 bonus)

(1) Algemeen theorie (total 2 punts)

a) 0,5 punt b) 0,5 punt c) 0,5 punt d) 0,5 punt

(2) Pressure gauge (total 2 punts)

missing units ~~[illegible]~~ −0,5
calculation error −0,25
general rule.

a) 1 punt ;

0,5 punt 0,5 punt

both modifying & interfering since slope & offset extrapolated at P=0 changes from 25°C to 35°C

b) ~~[illegible]~~ 1 punt

$$O(I) = (K + K_M I_M)\,I + a + K_I I_I$$

O: I_{out} (mA)

I: pressure p [b]

I_M: temp °C

I_I: temp. change °C

standard condition : $O(I) = KI + a$
$(I_M = I_I = 0)$

from table: $K = 3{,}1 \, \frac{mA}{b}$ → 0,5 punt
$a = 0{,}8 \, mA$ $(= 3{,}9 - 3{,}1)$

from table:

$$(K + K_M I_M) = 3,7\ \frac{mA}{b} \quad (1)$$

$$(a + K_I I_C) = -0,2\ mA \quad (2)$$

$$(1) \Rightarrow 3,1\frac{mA}{b} + K_M \cdot 10^{\circ}C = 3,7\frac{mA}{b} \Rightarrow \boxed{K_M = 0.06\ \frac{mA}{{}^{\circ}C \cdot b}}$$

$$(2) \Rightarrow 0.8\ mA + K_I \cdot 10^{\circ}C = -0,2\ mA \Rightarrow \boxed{K_I = -0,1\ \frac{mA}{{}^{\circ}C}}$$

0,5 pull

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Question (3) (total 2 pnts)

(a) $V_{out} = (K + K_m I_m)(F_{in} - K_F V_{out}) K_A$

$$\Rightarrow V_{out} = \frac{(K + K_m I_m) K_A}{1 + (K + K_m I_m) K_F K_A} \cdot F_{in}$$

(0,5 pnt)

(b) $(K + K_m I_m) K_F K_A >> 1$ $\left(\Rightarrow K_A >> \frac{1}{K K_F} \right)$

$$\Rightarrow V_{out} = \frac{F_{in}}{K_F}$$

(0,5 pnt)

(c) high gain neg. feedback: (1 pnt)

*) output not sensitive to interference effects.

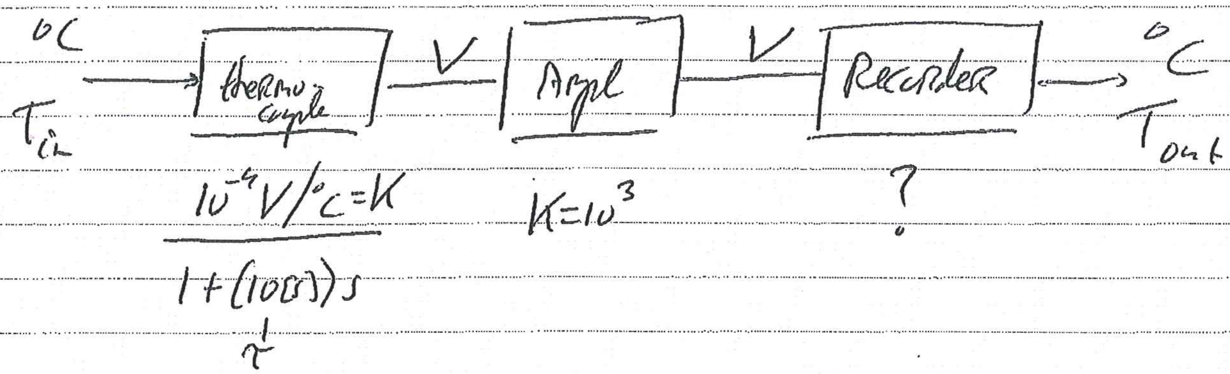
*) Amplifier can be unstable, as long as amplification large.

*) non-linearity in K, K_m, K_A eliminated as long as K_F part linear.

(Any of these answers gives points)

PoMS exam 23/01/2014

(4) temp. measurement system (2 pnts)



$$G_{TC}(s) = \frac{10^{-4}\,V/°C}{1+10s}\ ; \ G_A(s) = 10^3\ ; \ G_R = \dots$$

a) $$G_{total} = \frac{1}{1+12s+20s^2} = \frac{1}{(1+10s)(1+2s)} = G_{TC} \times G_A \times G_R$$

$$\Rightarrow G_R(s) = \frac{10\,°C/V}{(1+2s)}$$
$\quad \llcorner \tau_R = 2\ s$

0.5 pts

b) 7.0.7.
(1)

$$\frac{\Delta \tilde{T}_{out}}{\Delta \tilde{T}_{in}} = G(s) = \frac{1}{(1+10s)(1+2s)}$$

with $\Delta \tilde{T}_{in} = \frac{10^{\circ}C}{s} \Rightarrow \Delta \tilde{T}_{out} = 10 \times \frac{1}{s(1+10s)(1+2s)}$

(0,25 pts)

parts by fraction:

$$\frac{1}{s(1+10s)(1+2s)} = \frac{A}{s} + \frac{B}{(1+10s)} + \frac{C}{(1+2s)}$$

$$A(1+10s)(1+2s) + Bs(1+2s) + Cs(1+10s) = 1$$

$$s^2\underbrace{\left[20 \cdot A + 2B + 10C\right]}_{=0} + s\underbrace{\left[12A + B + C\right]}_{=0} + A = 1$$

$A = 1$

$$\Rightarrow \begin{cases} 12 + B + C = 0 \\ 20 + 2B + 10C = 0 \end{cases}$$

$B + C = -12$

$B + 5C = -10$

$-4C = -2$

$C = \frac{1}{2}$

(0,5 pts)

$B + \frac{1}{2} = -12$

$B = -12,5$ $\left(= -\frac{25}{2}\right)$

$$\Rightarrow \Delta \hat{T}_{uit} = 10\left[\frac{1}{s} - \frac{25/2}{1+10s} + \frac{1/2}{1+2s}\right] \; [°C]$$

$$\left(\frac{25/20}{\frac{1}{10}+s}\right) \qquad \left(\frac{1/4}{\frac{1}{2}+s}\right)$$

$$\Big\} \mathcal{L}^{-1}$$

$$\Delta T_{uit}(t) = 10\left[\mu(t) - \frac{25}{20} e^{-t/10} + \frac{1}{4} e^{-t/2}\right] \; [°C]$$

[s]

(0,25 punt)

c) z.o.z.

c) [0,5 pts total]

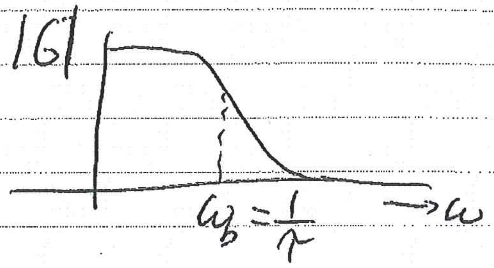
$$G(s) = \frac{1}{1+10s} \cdot \frac{1}{1+2s}$$

$$\tau_{tc} = 10\,[s] \qquad \tau_R = 2\,[s]$$

bandwidth defined:

$$|G(s=j\omega)| \geq \frac{1}{\sqrt{2}}$$

(0,25 pts)



Since $\tau_{tc} \gg \tau_R \Rightarrow \omega_b = \frac{1}{\tau_{tc}} = 0{,}1\ Hz$

"exact solution"

$$|G|^2 = \frac{1}{(1+10j\omega)(1+2j\omega)} \cdot \frac{1}{(1-10j\omega)(1-2j\omega)}$$

$$= \frac{1}{[1+100\omega^2][1+4\omega^2]} \leq \frac{1}{2}$$

(0,25 pts)

$\hookrightarrow \omega_b \approx 0{,}1\ Hz$

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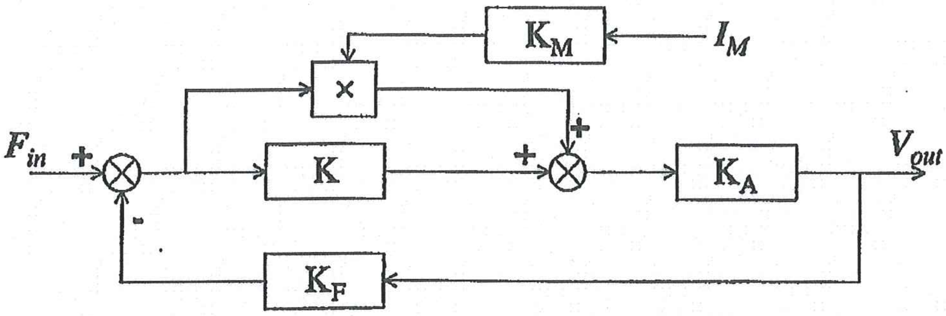

Figure 1: A high-gain negative feedback system.

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c) What choice for R_3 and R_4 is needed to improve significantly the linearity of the system and to obtain the relation

$$E_{Th} = V_S\left(\frac{R_0}{R_3}\right)\alpha T_1.$$

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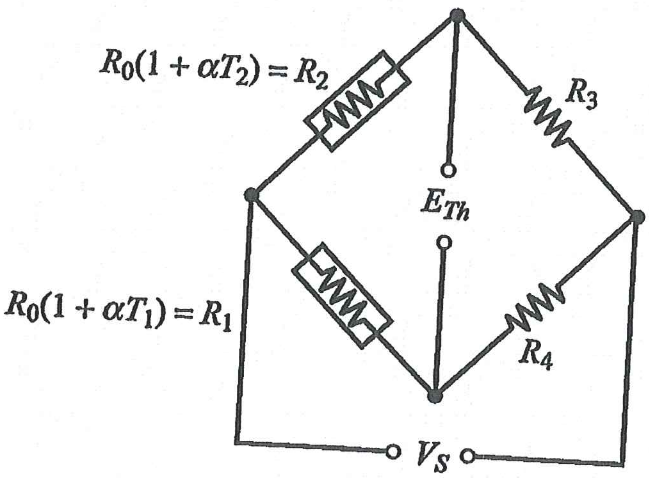


Figure 2: A two-element resistance sensor bridge.

PvMS exam 23/01/2014 Antwoord (model)

eenheid: 0,25 pnts, maximum score 10, max. pnts 11 (1 bonus)

(1) Algemene theorie (total 2 pnts)

a) 0,5 pnt b) 0,5 pnt c) 0,5 pnt d) 0,5 pnt

(2) Pressure gauge (total 2 pnts)

missing units ~~[illegible]~~ −0,5
calculation error −0,25
general rule.

a) 1 pnts ;

both modifying & interfering since slope (0,5 pnt) & offset (0,5 pnt) extrapolated at P=0 changes from 25°C to 35°C

b) ~~[illegible]~~ 1 pnt.

$$O(I) = (K + K_M I_M)\, I + a + K_I I_I$$

O: I_{out} (mA); I_M: temp °C; I: pressure p [b]; I_I: temp. change °C

standard condition : $O(I) = KI + a$
($I_M = I_I = 0$)

from table: $\boxed{K = 3{,}1 \frac{mA}{b} \quad a = 0{,}8\, mA}$ → 0,5 pnt

($= 3{,}9 - 3{,}1$)

from table:

$$(K + K_m I_m) = 3{,}7 \frac{mA}{b} \quad (1)$$

$$(a + K_I I_C) = -0{,}2\, mA \quad (2)$$

$$(1) \Rightarrow 3{,}1 \frac{mA}{b} + K_m \cdot 10°C = 3{,}7 \frac{mA}{b} \Rightarrow \boxed{K_m = 0.06 \frac{mA}{°C \cdot b}}$$

$$(2) \Rightarrow 0.8\, mA + K_I \cdot 10°C = -0{,}2\, mA \Rightarrow \boxed{K_I = -0{,}1 \frac{mA}{°C}}$$

0,5 pull

PdMS, 23/01/2014

Question 3 (total 2 pnts)

(a) $V_{out} = (K + K_m I_m)(F_{in} - K_F V_{out}) K_A$

$$\Rightarrow V_{out} = \frac{(K + K_m I_m) K_A}{1 + (K + K_m I_m) K_F K_A} \cdot F_{in}$$

(0,5 pnt)

(b) $(K + K_m I_m) K_F K_A >> 1 \quad \left(\Rightarrow K_A >> \frac{1}{K K_F} \right)$

$$\Rightarrow V_{out} = \frac{F_{in}}{K_F}$$

(0,5 pnt)

(c) high gain neg. feedback: (1 pnt)

*) output not sensitive to interference effects.

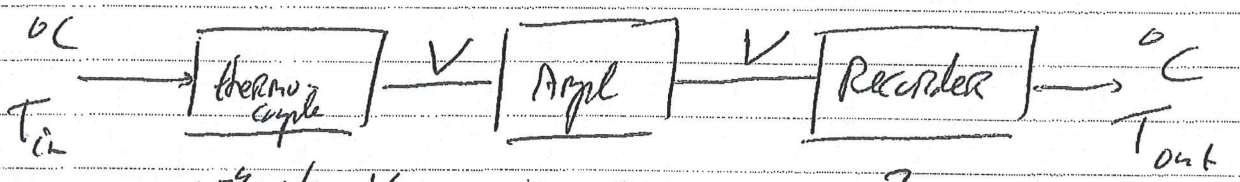
*) Amplifier can be unstable, as long as amplification large.

*) non-linearity in K, K_m, K_A eliminated as long as K_F part linear.

(Any of these answers gives points)

PUMS exam 23/01/2014

(4) temp. measurement system (2 pnts)



$$\frac{10^{-4}\,V/°C = K}{1+(10s)s} \qquad K=10^3 \qquad ?$$

τ

$$G_{TC}(s)=\frac{10^{-4}\,V/°C}{1+10s} \; ; \; G_A(s)=10^3 \; ; \; G_R = \dots$$

a) $$G_{total} = \frac{1}{1+12s+20s^2} = \frac{1}{(1+10s)(1+2s)} = G_{TC}\times G_A\times G_R$$

$$\Rightarrow G_R(s) = \frac{10\,°C/V}{(1+2s)}$$

$\llcorner \tau_R = 2\text{ s}$

0.5 pts

b) 7.0.7.

$$\frac{\Delta \tilde{T}_{out}}{\Delta \tilde{T}_{in}} = G(s) = \frac{1}{(1+10s)(1+2s)}$$

with $\Delta \tilde{T}_{in} = \frac{10^{\circ}C}{s} \Rightarrow \Delta \tilde{T}_{out} = 10 \times \frac{1}{s(1+10s)(1+2s)}$

(0,25 pts)

parts by fraction:

$$\frac{1}{s(1+10s)(1+2s)} = \frac{A}{s} + \frac{B}{(1+10s)} + \frac{C}{(1+2s)}$$

$$A(1+10s)(1+2s) + Bs(1+2s) + Cs(1+10s) = 1$$

$$s^2\underbrace{\left[20 \cdot A + 2B + 10C\right]}_{=0} + s\underbrace{\left[12A + B + C\right]}_{=0} + A = 1$$

$A = 1$

$$\Rightarrow \left.\begin{array}{l} 12 + B + C = 0 \\ 20 + 2B + 10C = 0 \end{array}\right\} \quad \begin{array}{l} B + C = -12 \\ B + 5C = -10 \\ \hline -4C = -2 \end{array}$$

(0,5 pts)

$\hookrightarrow C = \frac{1}{2}$

$\hookrightarrow B + \frac{1}{2} = -12$

$B = -12,5$ $\left(= -\frac{25}{2}\right)$

$$\Rightarrow \Delta \hat{T}_{out} = 10\left[\frac{1}{s} - \frac{25/2}{1+10s} + \frac{1/2}{1+2s}\right] \quad [{}^{o}C]$$

$$\downarrow \qquad\qquad \downarrow$$

$$\left(\frac{25/20}{\frac{1}{10}+s}\right) \qquad \left(\frac{1/4}{\frac{1}{2}+s}\right)$$

$$\Big\} \mathcal{L}^{-1}$$

[s]

$$\Delta T_{out}(t) = 10\left[\mu(t) - \frac{25}{20} e^{-t/10} + \frac{1}{4} e^{-t/2}\right] \quad [{}^{o}C]$$

(0,25 pkt)

c) Z.O.Z.

c) [0,5 pnt total]

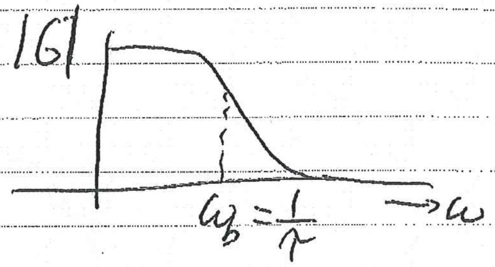
$$G(s) = \frac{1}{1+10s} \cdot \frac{1}{1+2s}$$

$$\tau_{tc} = 10\,[s] \qquad \tau_R = 2\,[s]$$

bandwidth defined:

$$|G(s=j\omega)| \geq \frac{1}{\sqrt{2}}$$

(0,25 pnt)



Since $\tau_{tc} \gg \tau_R \Rightarrow \omega_b = \frac{1}{\tau_{tc}} = 0{,}1$ Hz

"exact solution"

$$|G|^2 = \frac{1}{(1+10j\omega)(1+2j\omega)} \cdot \frac{1}{(1-10j\omega)(1-2j\omega)}$$

$$= \frac{1}{[1+100\omega^2][1+4\omega^2]} \leq \frac{1}{2}$$

(0,25 pnt)

$\Rightarrow \omega_b \approx 0{,}1$ Hz

PG15, 23/01/2014

5 (total: 3 pnts (1 bonus))

(a)
$$E_{Th} = \frac{R_1R_3 - R_2R_4}{(R_1+R_4)(R_2+R_3)}V_s \quad \text{(Wheatstone bridge)}$$

$T_1 = T_2$ $(=0°C)$ $\Rightarrow$ $R_1 = R_2$, hence $R_3 = R_4$ then $E_{Th} = 0$ for that condition.

(0,5 pnts)

b)
$$E_{Th} = \left(\frac{1}{1+\frac{R_4}{R_1}} - \frac{1}{1+R_3/R_2}\right)V_s$$

$$= \left(\frac{1}{1+\frac{100}{100(1+\alpha T_1)}} - \frac{1}{1+100/100}\right)V_s$$

$$= \left(\frac{(1+\alpha T_1)}{(1+\alpha T_1)+1} - \frac{1}{2}\right)V_s = \left(\frac{(1+\alpha T_1)}{(2+\alpha T_1)} - \frac{1}{2}\right)V_s$$

$T_1 = 0 \Rightarrow E_{Th} = 0$ (balanced)

$$T_1 = 50°C \Rightarrow E_{Th} = \left(\frac{(1+\overset{0,25}{\cancel{}})}{(2+0{,}25)} - \frac{1}{2}\right)V_s \equiv 1\,V$$

$\hookrightarrow \boxed{V_s = 18\,V}$ (0,5 pnts)

@ T = 25°C

$$\Rightarrow E_{Th} = \left(\frac{\left(1+\frac{1}{8}\right)}{\left(2+\frac{1}{8}\right)} - \frac{1}{2} \right) 15V = 0{,}53\,[V]$$

for linear response: $E_{Th}^{ideal} = 0{,}5V$

hence non-linearity: $\frac{(0{,}53-0{,}5)}{~~1{,}5~~\,1\,V} \times 100\% = ~~\ldots~~\, 3\,\%$

~~of~~ (full span)

(0,5 pnts)

c) $$E_{Th} = \left[\left(\frac{1}{1+\underbrace{\frac{R_4(=R_3)}{R_0(1+\alpha T_1)}}_{>>1}} \right) - \left(\frac{1}{1+\underbrace{\frac{R_3(=R_4)}{R_0(1+\alpha T_2)}}_{>>1}} \right) \right] V_s$$

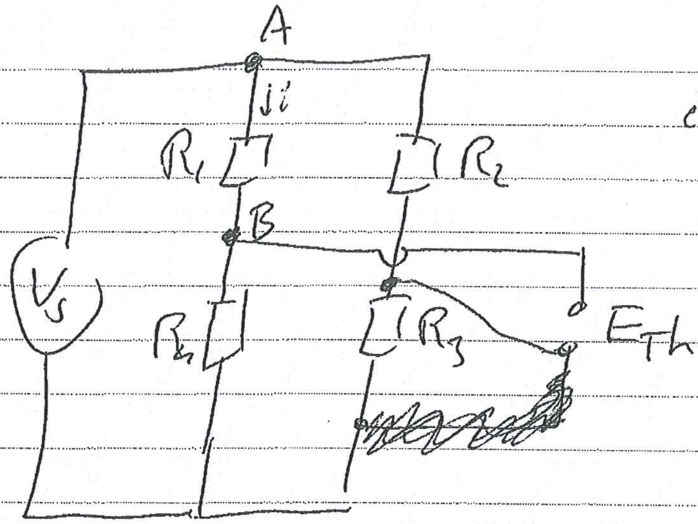
$$\approx \left[\frac{(1+\alpha T_1)}{R_3/R_0} - \frac{(1+\alpha T_2)}{R_3/R_0} \right] V_s$$

$$= V_s \left(\frac{R_0}{R_3} \right) \alpha \left[\underbrace{T_1 - T_2}_{\approx 0} \right]$$

(0,5 pnts)

so, take $R_3 = R_4 >> R_0$!

Price: sensitivity is very small since R_0/R_3 becomes small d)



$$i = \frac{V_s}{R_1 + R_4}$$

$$\hookrightarrow V_{AB} = i R_1$$

$$= V_s \left[\frac{R_1}{R_1 + R_4} \right]$$

0,5 pnt

$$V_{AB} = V_A - V_B = V_s - V_s \frac{R_4}{R_1 + R_4} = V_s \left(\frac{R_1}{R_1 + R_4} \right)$$

power through R_1 : $P = \dfrac{V_{AB}^2}{R_1} = V_s^2 \dfrac{R_1}{\underbrace{(R_1+R_4)^2}_{\approx R_4}} = V_s^2 \dfrac{R_1}{R_4^2}$

maximum when R_1 maximum, e.g. $T = 50°C$ 0,5 pnt

$$P = (12)^2 \left[\frac{100(1+0{,}25)}{(10 \cdot 10^3)^2} \right] \quad [W]$$

$$= 144 \cdot \left[\frac{125}{10^8} \right] = 1{,}8 \cdot 10^{-4} \ W$$

$$= \underline{\underline{0{,}18 \ mW}}$$