Student name:

Student number:

Examination cover sheet
(to be completed by the examiner)

Course name: Sensing, Computing, Actuating   Course code: 5AIB0

Date: 14-8-2018

Start time: 9:00   End time : 12:00

Number of pages: 7

Number of questions: 3

Maximum number of points/distribution of points over questions: 90

Method of determining final grade: divide total of points by 9

Answering style: open questions

Exam inspection: make appointment via email with the responsible lecturer

Other remarks:

Instructions for students and invigilators

Permitted examination aids (to be supplied by students):

☐ Notebook
☑ Calculator
☐ Graphic calculator
☐ Lecture notes/book
☐ One A4 sheet of annotations
☐ Dictionar(y)(ies). If yes, please specify:
☐ Other:

Associated with the Central Examination Regulations

Final Exam
5AIB0 Sensing, Computing, Actuating
14-8-2018, 9:00-12:00

- This final exam consists of 3 questions for which you can score at most 90 points. The final grade for this exam is determined by dividing the number of points you scored by 9.

- The solutions to the exercises should be clearly formulated and written down properly. Do not only provide the final answer. Explain your choices and show the results of intermediate steps in your computation.

- The use of a simple calculator is allowed. No graphical calculator or laptop may be used during the exam.

Formulae sheet

Characteristic temperature of material: $B_{T_1/T_2} = \frac{ln\left(\frac{R_2}{R_1}\right)}{\frac{1}{T_1} - \frac{1}{T_2}}$

Resistance: $R = \frac{m}{ne^2\tau}\frac{l}{A} = \rho\frac{l}{A}$

Strain: $\epsilon = \frac{dl}{l}$

Stress: $\sigma = \frac{F}{A} = E\frac{dl}{l}$

Poisson's ratio: $v = -\frac{dt/t}{dl/l}$

Change in specific resistance due to volume change (for metals): $\frac{d\rho}{\rho} = C\frac{dV}{V}$

Change in resistance due to strain: $\frac{dR}{R} = G\epsilon$

Capacitance of flat plate capacitor: $C = \frac{q}{V} = \epsilon_0\epsilon_r\frac{A}{d}$

Capacitance of cylindrical capacitor: $C = \frac{q}{V} = \epsilon_0\epsilon_r\frac{2\pi\cdot l}{ln(b/a)}$

Energy stored in capacitor: $E = \frac{C\cdot V^2}{2}$

Reluctance: $\Re = \frac{1}{\mu\mu_0}\frac{l}{A}$

Inductance: $L = \frac{N\cdot\Phi}{i} = \frac{N^2}{\Re}$

Flux: $\Phi = \mathbf{B} \times \mathbf{S}$

Magneto-motive force: $F_m = \Phi \cdot \Re = N \cdot i$

Amplitude response of Butterworth LPF: $|H(f)| = \frac{1}{\sqrt{1+\left(\frac{f}{f_n}\right)^{2n}}}$

Sideways force on electron moving through magnetic field: $\mathbf{F} = q \cdot \mathbf{v} \times \mathbf{B}$

Transverse Hall potential: $V_H = \frac{1}{N\cdot c\cdot q}\frac{i\cdot B}{d}sin(\alpha)$

Radius of warping of bimetal sensor: $r \approx \frac{2j}{3(\alpha_x-\alpha_y)(T_2-T_1)}$

Displacement of bimetal sensor: $\Delta = r(1 - cos(\frac{180L}{\pi r}))$

Flow velocity and temperature difference: $v = \frac{K}{\rho}\left(\frac{e^2}{R_S}\frac{1}{T_s-T_0}\right)^{1.87}$

Voltage across P-N junction (quality factor 1): $V = \frac{kT}{q}ln\left(\frac{I}{I_0}\right)$

Saturation current through PN-junction (quality factor 1): $I_0 = BT^3e^{-E_g/kT}$

Thomson effect: $Q = I^2 \cdot R - I \cdot \sigma\frac{dT}{dx}$

Peltier coefficient: $\pi_{AB}(T) = T \cdot (\alpha_A - \alpha_B) = -\pi_{BA}(T)$

Exercise 1: exhaust gas temperature measurement **(30 points)**

It is necessary to change the ratio between fuel and air in a combustion engine to maximize the efficiency of the engine. The objective is to keep the temperature of the gasses going through the exhaust pipe within a certain temperature range. Because of the high temperature of these gases, it is necessary to use a thermocouple to measure this temperature. A thermocouple can only measure a temperature difference. Therefore it is necessary to also add a reference sensor to the circuit. This sensor is then used to measure the absolute temperature at the reference junction.

The thermocouple in Figure 1 contains a reference junction compensation based on a RTD temperature sensor. The output voltage of this sensor (v_{ref}) is given by the following transfer function: $v_{ref} = 10mV/°C \cdot T_a$ with T_a the environmental temperature at the reference junction. The output of the reference temperature sensor is connected to the reference input of the instrumentation amplifier. It holds for this instrumentation amplifier:

$$v_o - v_{ref} = \left(1 + \frac{2R_2}{R_1}\right)\frac{R_4}{R_3}(v_2 - v_1) = (1 + G)\,k\,(v_2 - v_1)$$

The ratio of the resistors in the instrumentation amplifier is equal to: $k = R_4/R_3 = 1$. The thermocouple itself is a J-type (Cn/Fe) thermocouple with a sensitivity $S_J = 54\mu V/K$.
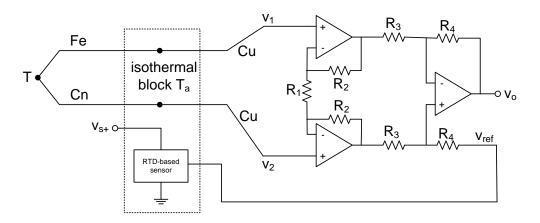

Figure 1: Compensation with a RTD-based sensor and instrumentation amplifier.

(5p) (a) There are three important law that you can use when analysing thermocouples, namely the law of the homogeneous circuits, the law of intermediate metals, and the law of intermediate temperatures. Show using these laws that the voltage across the thermocouple shown in Figure 1 is equal to:

$$v_2 - v_1 = V_T - V_{T_a} = S_J \cdot (T - T_a)$$

Hint: The Seebeck coefficient $\alpha_{Cn/Fe}$ of a J-type thermocouple is equal to: $\alpha_{Cn/Fe} = S_J$.

(5p) (b) What gain, G, should the instrumentation amplifier have to get an output voltage v_o that is independent of the environmental temperature?
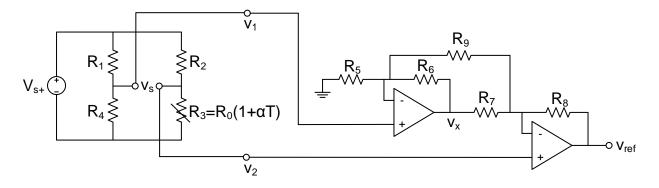
Exercise continues on next page

Figure 2: Implementation of "RTD-based sensor" block of Figure 1.

(5p) (c) The circuit shown in Figure 2 is used to generate the reference voltage v_{ref} for the thermocouple sensor shown in Figure 1. In other words, Figure 2 shows the internals of the block "RTD-based sensor" in Figure 1. Assume that the supply voltage v_{s+} is equal to 5 V. Assume further that resistor R_3 is a temperature dependent resistor (RTD) of type PT100. Its relation between temperature and resistance (transfer function) can be approximated with the following linear equation: $R_3(T) = R_0(1 + \alpha T)$, with R_0 equal to 100Ω and $\alpha = 0.004/°C$. Assume also that $R_4 = R_5 = R_6 = R_7 = R_8 = R_0$ and $R_1 = R_2 = k \cdot R_0$. What resistance should the resistor R_2 have to ensure that the "RTD-based sensor" has a sensitivity of $10mV/°C$?

(5p) (d) The operation of a temperature dependent resistor (RTD) is based on the thermo-resistive effect. Explain briefly (maximal 200 words) how this effect works in metals.
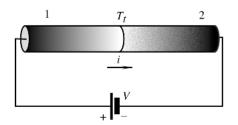

Figure 3: Peltier effect in single junction.

(5p) (e) Figure 3 shows a single junction of two different materials. Explain (in maximally 200 words) why the Peltier effect results in the production or liberation of energy at a junction when a current is passed through this junction.

(5p) (f) Give at least three reasons why we prefer transducers who produce a signal in the electrical domain over transducers that produce a signal in any of the other signal domains.

Exercise 2: Active suspension **(30 points)**

An active suspension system measures the displacement x between the wheels and the car body. This can be done using a linear variable differential transformer (LVDT). The sensor uses the magnetic coupling between a primary and two secondary coils to measure the displacement of a ferromagnetic core. Figure 4 shows the electrical equivalent circuit of a LVDT sensor that is connected to a voltage supply v_r with a frequency of 5 Hz and an amplitude of 10 V. There is no load connected to the output of the sensor. The LVDT has a sensitivity S of 250 $(\mu V/V)/\mu m$. The output voltage of the LVDT is equal to:

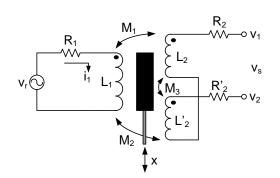$$v_s = v_2 - v_1 = S \cdot x \cdot v_r$$

Figure 4: Measuring a displacement using an LVDT.

(5p) (a) Show that the output voltage of the sensor, v_s, is equal to:

$$v_s = \frac{s k_x x v_r}{s L_1 + R_1}$$

with $(M_2 - M_1) = k_x x$.

(5p) (b) Assume that the resistor R_1 has a resistance of 250 Ω and the inductor L_1 has an inductance of 40 mH. What is the value of the coupling coefficient k_x?

(5p) (c) A driver moves over a speed bump in 1 second causing the LVDT to move from a position $x = -15\ \mu m$ to a position $x = +15\ \mu m$. Draw the output voltage v_s as a function of time t. (Clearly show the dimensions on both axis.)

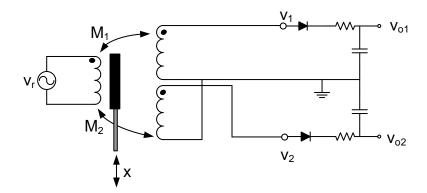<div align="right">**Exercise continues on next page**</div>

Figure 5: Double-sided rectifier with low-pass filter.

(3p) (d) The output signal of the LVDT shown in Figure 4 is connected to a double-sided rectifier with a low-pass filter as is shown in Figure 5. Draw the output voltage, $v_{o2} - v_{o1}$, when the position of the core in the LVDT changes in 1 second from $x = -15\ \mu m$ to $x = +15\ \mu m$.

(4p) (e) The output of the sensor (v_s in Figure 4) can be connected directly to an AD converter. Alternatively the output of the sensor could be connected to a phase sensitive detector whose output is then connected to the AD converter. Give at least one reason why we prefer to use a phase sensitive detector in front of the AD converter instead of directly connecting the output of the sensor to the AD converter.

(4p) (f) Instead of using an inductive displacement sensor, you could also use a resistive displacement sensor. Give at least two advantages of using an inductive displacement sensor over a resistive displacement sensor.

(4p) (g) An LVDT measures the rotation of an object through the change in coupling between a primary and two secondary coils. Another way to measure a rotation would be to use a Hall effect sensor. Explain the operation of a Hall effect sensor. Clearly indicate how you can use the sensor to measure a rotation.

Exercise 3: temperature sensor   **(30 points)**

A resistive temperature detector (RTD) can be used to measure the temperature of an object. Figure 6 shows a bridge circuit with an RTD which is exposed to a temperature T. This temperature will be in the range [-30°C, 80°C]. The RTD is a PT100 sensor with $R_0 = 100\ \Omega$ and $\alpha = 0.004/°C$ at 0°C.
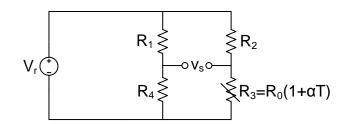

Figure 6: Bridge circuit with a RTD temperature sensor.

(5p) (a) Show that output voltage v_s of the sensor circuit is equal to:

$$v_s = -\frac{k\alpha T}{(k+1)(k+1+\alpha T)}V_r$$

, with $k = R_1/R_4 = R_2/R_0$.

(7p) (b) What ratio k should the resistors R_2/R_0 have to ensure that the non-linearity error is less then 0.8% of the reading while maximizing the sensitivity?

(7p) (c) Assume that $k = 38.7$. Assume further that the dissipation constant of the environment $\delta = 1$ mW/K. What value should the supply voltage V_r have to keep the self-heating below 0.002% of the full-scale output (FSO)?

(5p) (d) The operation of a temperature dependent resistor (RTD) is based on the thermo-resistive effect. Explain briefly (maximal 200 words) how this effect works in metals.
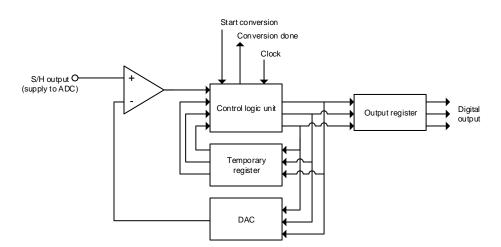

Figure 7: Successive approximation AD converter.

(6p) (e) The output voltage v_s of the bridge circuit shown in Figure 6 can be digitized using a successive approximation AD converter like the one shown schematically in Figure 7. Explain (maximal 500 words) how the successive approximation AD converter works. You may also draw a figure to illustrate its operation.