Technische Universiteit **Eindhoven** University of Technology

Student name:

Student number:

# Examination cover sheet

(to be completed by the examiner)

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

Date: 23-6-2015

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

Number of pages: 8

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:

# Final Exam
# 5AIB0 Sensing, Computing, Actuating
# 23-6-2015, 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: throttle position sensor** **(30 points)**

The driver of a car can control the power delivered by the engine through the throttle pedal. When moving this pedal, the driver changes the amount of fuel or the fuel/air mixture. This allows the driver to control the speed of the car. Traditionally, the throttle pedal has been connected with a carburetor valve using a so called bowden cable. Modern cars use a “drive-by-wire” system that replaces this cable with an electric system. These systems use a sensor to sense the position of the throttle pedal. One option would be to use a resistive displacement sensor such as the one shown in Figure 1. This sensor can be used to measure linear displacements of an object. The sensor consists of a variable resistor $R_T$, a fixed resistor $R_s = R_T/a = 3000\ \Omega$ and a constant voltage supply $V_r = 9$ V. The sensor is connected to a measurement circuit with a purely resistive impedance $R_m = R_T/b$ with a resistance of 3000 $\Omega$ (i.e., $a = b$). This measurement load causes a loading error in the output voltage $v_m$ of the sensor.

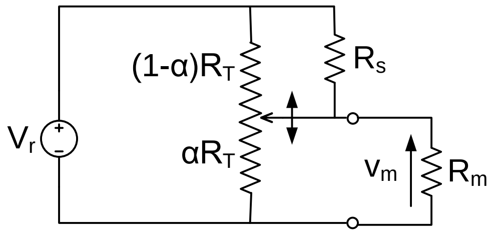


Figure 1: Displacementsensor with processing circuit.

(5p) (a) Show that the output voltage $v_m$ of the circuit shown in Figure 1 is equal to:

$$v_m = \frac{\alpha\,(1 + a\,(1-\alpha))}{1 + \alpha\,(1-\alpha)\,(a+b)} V_r$$

(5p) (b) Show that the relative error in the output voltage of the sensor due to the loading circuit $R_m$ is equal to:

$$\epsilon = \left| \frac{\alpha\,(1-\alpha)\,b}{1 + \alpha\,(1-\alpha)\,(a+b)} \right|$$

(5p) (c) A certain application requires that the relative error of the sensor at $\alpha = 0.75$ is not more then 3%. What value should the resistor $R_T$ to ensure that this constraint is met?

(2p) (d) Instead of using a resistive displacement sensor, you could also use an inductive displacement sensor. Give at least one advantage of using an inductive displacement sensor over a resistive displacement sensor.

**Exercise continues on next page**

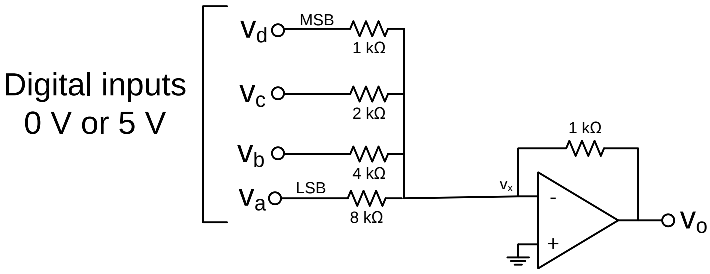


Figure 2: DA converter using summing op-amp.

(5p) (e) A summing DA converter is shown in Figure 2. Which binary input has been applied to the DA converter if it has an output voltage $v_o$ of 1.9V?

(8p) (f) Give a definition (maximally 100 words) for the following terms:

- Transducer
- Sensor
- Sensitivity of a sensor
- Transfer function of a sensor

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

An active suspension system measures the displacement 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 3 shows the electrical equivalent circuit of a LVDT sensor that is connected to a voltage supply $v_1$ with a frequency of 1000 Hz and an amplitude of 10 V. At this excitation frequency, a phase shift of +45° occurs between the input voltage and the output voltage of the sensors. There is no load connected to the output of the sensor.

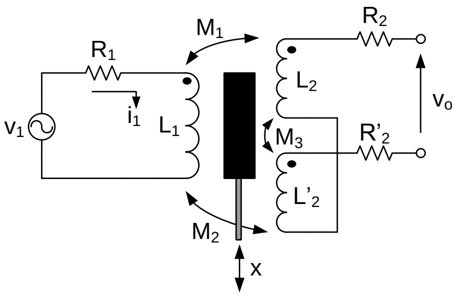


Figure 3: LVDT sensor.

(5p) (a) Show that the output voltage $V_o$ is equal to:

$$V_o = \frac{j\omega k_x x V_1}{j\omega L_1 + R_1}$$

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

(5p) (b) A sinusoidal voltage supply $v_1$ with a frequency of 1000 Hz and an amplitude of 10 V is connected to the primary winding of the LVDT sensor shown in Figure 3. At this excitation frequency, a phase shift of +45° occurs between the input voltage and the output voltage of the sensors. The sensor has a sensitivity of 0.1 V/mm. Assume that the ferromagnetic core moves with a triangular movement of 100 Hz between $x = -20$ mm and $x = +20$ mm. Draw the excitation voltage on the primary winding ($v_1(t)$), the displacement ($x(t)$) of the ferromagnetic core, and the output voltage ($v_o(t)$) of the sensor. (Clearly show the dimension and units on all axis.)

(5p) (c) The phase shift $\phi$ between the input voltage $V_1$ and the output voltage $V_o$ is equal to:

$$\phi = 90° - arctan\left(\frac{2\pi \cdot f \cdot L_1}{R_1}\right)$$

Assume that the inductance of the primary winding of the LVDT is equal to 40 mH, i.e, $L_1 = 40$ mH. Assume further that the excitation voltage $V_1$ has a frequency of $f = 1000$ Hz. In this situation, a phase shift $\phi$ of +45° occurs between the input and output voltage of the sensor. What is the resistance of the resistor $R_1$?

(5p) (d) Assume that the excitation voltage $V_1$ has a frequency of 1600 Hz, the primary winding has a resistance $R_1$ of 251 Ω and an inductance $L_1$ of 40 mH. The frequency at which a certain phase shift occurs can be changed by adding an additional resistor $R'$ in series or in parallel to the primary input of the sensor. What resistance should the resistor $R'$ have such that a phase shift of +45° occurs at a frequency of 1600 Hz?

**Exercise continues on next page**

(5p) (e) Figure 4 shows a processing circuit in which the output of the LVDT is connected to an instrumentation amplifier who in turn is connected to a single-sided rectifier with low-pass filter. Is it possible to reconstruct from the output signal $v_o$ the direction of the movement (positive or negative direction)? (Explain your answer.)

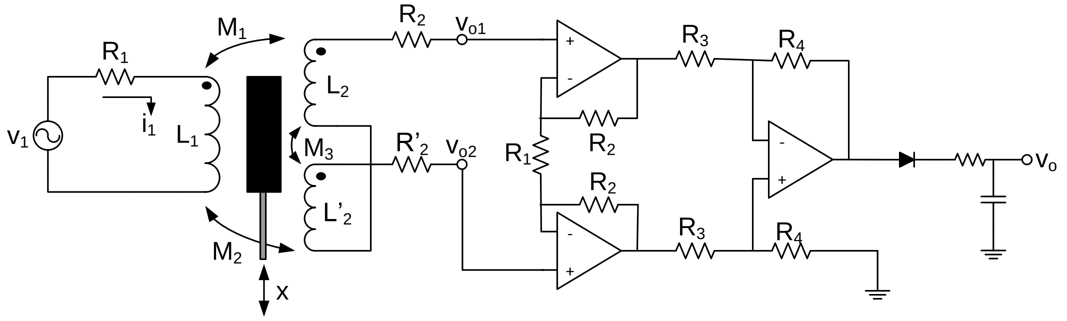


Figure 4: Single-sided rectifier with low-pass filter.

(5p) (f) A LVDT measures the displacement of an object through the change in coupling between a primary and two secondary coils. Another way to measure a displacement 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 displacement.

**Exercise 3: 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 5 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:

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

The ratio of the resistors in the instrumentation amplifier is equal to: $k = R_4/R_3 = R_2/R_1 = 1$. The thermocouple itself is a J-type (Cn/Fe) thermocouple with a sensitivity $S_J = 54\mu V/K$.

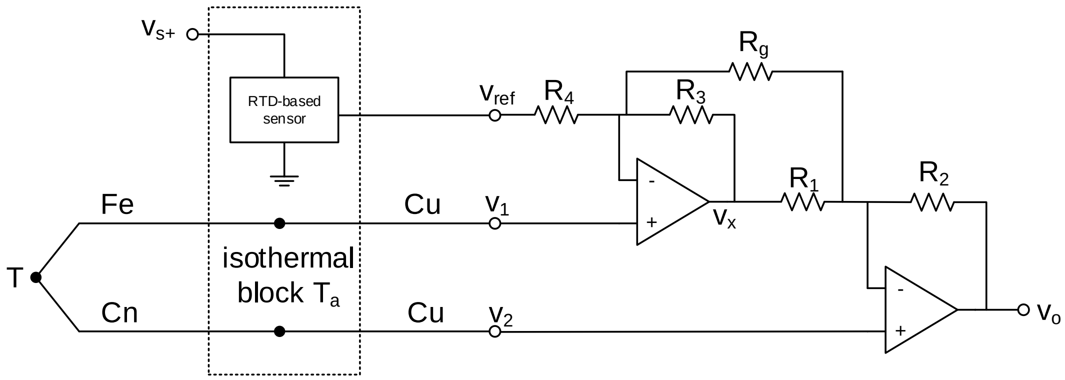


Figure 5: Compensation with a RTD-based sensor and instrumentation amplifier.

(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 5 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**

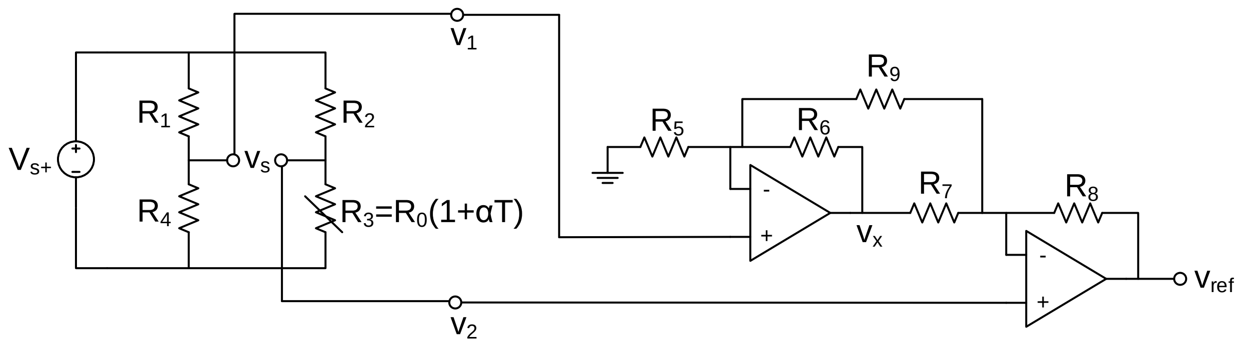


Figure 6: Implementation of "RTD-based sensor" block of Figure 5.

(5p) (c) The circuit shown in Figure 6 is used to generate the reference voltage $v_{ref}$ for the thermocouple sensor shown in Figure 5. In other words, Figure 6 shows the internals of the block "RTD-based sensor" in Figure 5. 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 $\alpha = 0.004/°\text{C}$. Assume also that $R_4 = R_5 = R_6 = R_7 = R_8 = R_9 = R_0$ 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) Does the RTD-based circuit show a non-linear relation between temperature and output voltage? If so, how could these non-linearities be reduced. (Explain your answer)

(5p) (e) 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.

(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.