TU/e 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: 11-8-2015	
Start time: 13:30	End time : 16:30
Number of pages: 12	
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:

Important:

- examinees are only permitted to visit the toilets under supervision
- it is not permitted to leave the examination room within 15 minutes of the start and within the final 15 minutes of the examination, unless stated otherwise
- examination scripts (fully completed examination paper, stating name, student number, etc.) must always be handed in
- the house rules must be observed during the examination
- the instructions of examiners and invigilators must be followed
- no pencil cases are permitted on desks
- examinees are not permitted to share examination aids or lend them to each other

During written examinations, the following actions will in any case be deemed to constitute fraud or attempted fraud:

- using another person's proof of identity/campus card (student identity card)
- having a mobile telephone or any other type of media-carrying device on your desk or in your clothes
- using, or attempting to use, unauthorized resources and aids, such as the internet, a mobile telephone, etc.
- using a clicker that does not belong to you
- having any paper at hand other than that provided by TU/e, unless stated otherwise
- visiting the toilet (or going outside) without permission or supervision

Final Exam
5AIB0 Sensing, Computing, Actuating
11-8-2015, 13:30-16:30

- 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: resistive pressure sensor **(30 points)**

Strain gauges are used amongst others to measure pressure. Figure 1 shows two strain gauges that are attached to a thin metal strip (E = $200 \cdot 10^9$ N/m^2). The strain gauges are combined with two resistors with a fixed value into a complete bridge. When unloaded, each strain gauge has a resistance of 200 Ω. The fixed resistors also have a resistance of 200 Ω. The strain gauges have a gage factor of 2.00. To prevent damage to the strain gauges, the maximal current through them should be limited to 25 mA.

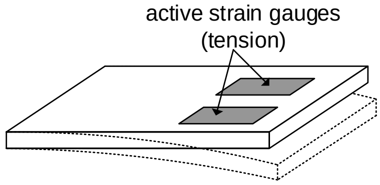

Figure 1: Metal strip with two active strain gauges.

The two strain gauges and the two fixed resistors are connected in a bridge circuit with a voltage supply V_r. The electrical equivalent circuit of this sensor is shown in Figure 2.

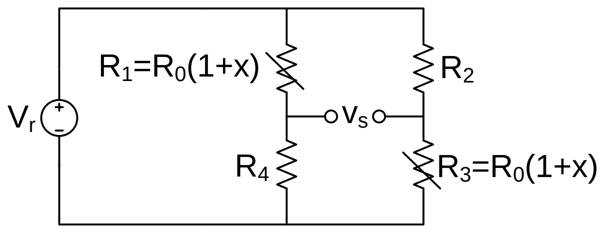

Figure 2: Bridge circuit with two strain gauges.

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

$$v_s = -\frac{x}{2+x} V_r$$

(2p) (b) Does the sensor circuit shown in Figure 2 show a non-linear response when pressure is applied to the sensor? (Explain your answer)

(5p) (c) What value should the voltage supply V_r have to maximize the sensitivity of the sensor circuit shown in Figure 2 for a change in x?

(5p) (d) Show that the output voltage v_s of the sensor circuit shown in Figure 2 is equal to -5.00 mV when a pressure of $100 \cdot 10^6$ N/m^2 is applied to the metal strip and $V_r = 10$ V.

Exercise continues on next page

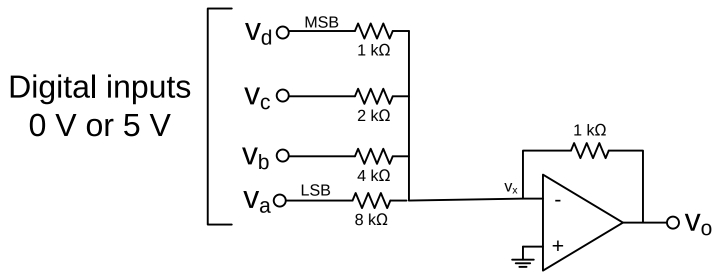

Figure 3: DA converter using summing op-amp.

(5p) (e) A summing DA converter is shown in Figure 3. Which binary input has been applied to the DA converter if it has an output voltage v_o of -3.8V?

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

A resistive temperature detector (RTD) can be used to measure the temperature of an object. Figure 4 shows a resistive divider circuit with an RTD which is exposed to a temperature T. This temperature will be in the range $[0°C,\ 100°C]$. The RTD is a PT100 sensor with $R_0 = 100\ \Omega$ and $\alpha = 0.004/°\mathrm{C}$ at 0°C.

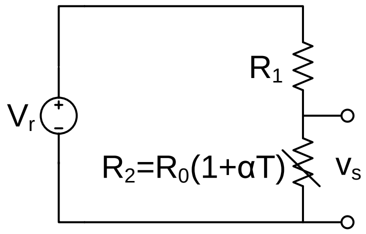

Figure 4: Resistive divider circuit with a RTD temperature sensor.

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

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

, with $k = R_1/R_0$.

(5p) (b) Show that sensitivity of the sensor circuit is equal to:

$$S = \frac{\alpha k}{(1+\alpha T+k)^2} V_r$$

(5p) (c) Show that relative non-linearity error of the sensor circuit is equal to:

$$\epsilon = \left| \frac{-\alpha T}{k+1+\alpha T} \right|$$

(5p) (d) What ratio k should the resistors R_1/R_0 have to ensure that the non-linearity error is less then 0.8% of the reading while maximizing the sensitivity?

(5p) (e) Assume that $k = 48.6$. Assume further that the dissipation constant of the environment $\delta = 7$ mW/K. What value should the supply voltage V_r have to keep the self-heating below 0.02% of the full-scale output (FSO)?

(5p) (f) 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.

Exercise 3: Electronic Stability Progam **(30 points)**

ESP assists a driver to keep a vehicle on the road during dangerous driving conditions. For this purpose, the ESP system uses a large number of sensors in the vehicle. One of these sensors measures the angle of the steering-wheel and steering-column and the speed with which the driver changes this angle (note that one sensor measures both quantities). The RVDT (rotary variable differential transducer) from Figure 5 can be used to measure the angle (and its rate of change). When the driver moves the steer from the central position ($\Theta = 0°$) to the left or to the right, then this will lead to a change in the output voltage of the sensor. This electrical signal can then be send to the ESP computer. The primary winding of this RVDT is connected to a voltage supply that produces a sinusoidal voltage with an amplitude of 5V with a frequency of 10 Hz. The RVDT has a sensitivity S of 100 μV/(°/V). The output voltage of the RVDT is equal to:

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

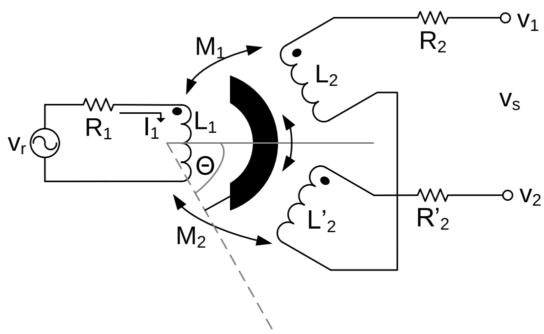

Figure 5: Measuring an angle using an RVDT.

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

$$v_s = \frac{j\omega k_\Theta \Theta v_r}{j\omega L_1 + R_1}$$

with $(M_2 - M_1) = k_\Theta \Theta$.

(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_Θ?

(5p) (c) A driver moves the steer in 1 second from an angle $\Theta = -20°$ to an angle $\Theta = +20°$. Draw the output voltage v_s as a function of time t. (Clearly show the dimensions on both axis.)

Exercise continues on next page

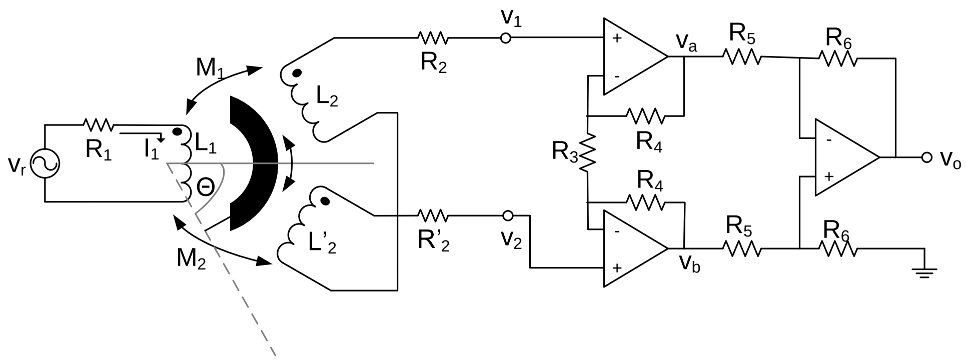

Figure 6: RVDT with instrumentation amplifier.

(5p) (d) The signal coming from the RVDT is too weak to be directly send to the ESP computer. The signal should first be amplified. For this purpose, the sensor from Figure 5 is connected to an instrumentation amplifier. The resulting circuit is shown in Figure 6. The instrumentation amplifier uses three operational amplifiers. You may assume that these op-amps show an ideal behaviour. Show that the output voltage v_o of the instrumentation amplifier in Figure 6 is equal to:

$$v_o = \left(1 + \frac{2R_4}{R_3}\right) \frac{R_6}{R_5} \frac{j\omega k_\Theta \Theta v_r}{j\omega L_1 + R_1}$$

(5p) (e) Assume that the resistors R_4, R_5, and R_6 in the instrumentation amplifier from Figure 6 have a resistance of 10 Ω. What resistance should the resistors R_3 have such that the amplitude of the output voltage v_o is equal to 0 V when $\Theta = 0°$ and 5 V (peak) when $\Theta = 20°$?

(5p) (f) A phase sensitive detector can be used to recover the magnitude and direction of the rotation of the sensor core. In stead of a phase sensitive detector, it is also possible to connect the output signal of the RVDT to a double-sided rectifier with a low-pass filter as is shown in Figure 7. Is it possible to reconstruct from the output signal ($v_{o2} - v_{o1}$) the direction (positive or negative angle)? (Explain your answer.)

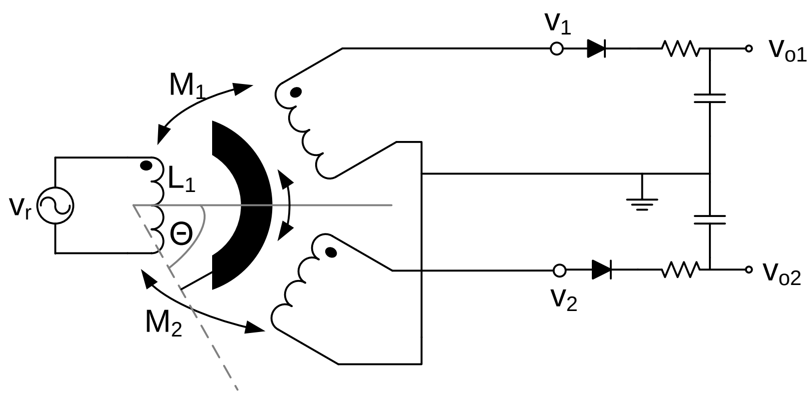

Figure 7: Double-sided rectifier with low-pass filter.