GLASGOW COLLEGE UESTC

Main Exam Paper

Electronic System Design 3 (UESTC 3003)

Date: 29th Dec. 2020
Time: 19:00pm - 21:00pm

Attempt all PARTS. Total 100 marks

Use one answer sheet for each of the questions in this exam.

Make sure that your University of Glasgow and UESTC Student Identification Numbers are on all answer sheets.

<u>An electronic calculator may be used</u> provided that it does not allow text storage or display, or graphical display.

All graphs should be clearly labelled and sufficiently large so that all elements are easy to read.

The numbers in square brackets in the right-hand margin indicate the marks allotted to the part of the question against which the mark is shown. These marks are for guidance only.

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Q1 A specialised differential weighing machine designed to measure the difference in weight applied to two sensors is shown in Figure Q1a. Sensor node **Sens1** and sensor node **Sens2** are connected as shown in the diagram. If the force applied to each sensor is equal and within the linear operating range of the instrument, the output voltage is zero. However, if the forces are not equal and (F1>F2) a negative output voltage is generated at (*Vout*) but if (F1<F2) then a positive output appears at (*Vout*); thus the instrument shows the difference in the weight being applied at the two sensors (F2 – F1).

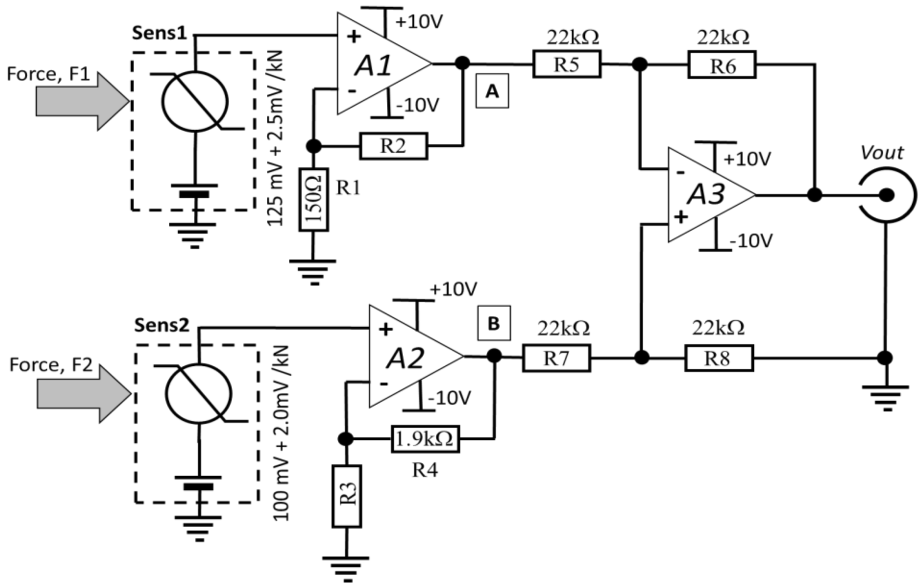

Figure Q1a: Differential weight detector schematic

The circuit consists of two non-inverting buffer amplifiers (*A1*, *A2*) with adjustable gain followed by a difference amplifier circuit around *A3*.

You may assume that all the operational amplifiers are of good quality with negligible offset voltage, offset current, and bias current, and have high gain. They are also capable of output signal swings up to the power rails (+/- 10V).

The sensors used have a DC offset plus a sensitivity measured in mV /kN. Due to production variations, sensors can vary as much as 20% from each other so these variations in sensitivity must be compensated for by adjusting the gain of the buffer amplifiers during manufacture. In the diagram, sensor **Sens1** has a sensitivity of (125mVDC + 2.5mV /kN) while sensor **Sens2** has a sensitivity of (100mVDC + 2.0mV /kN).

(a) Calculate the values of R2 and R3 such that the no load signal appearing at nodes '**A**' and '**B**' are identical and = 2.0V. Show all workings and state any assumptions. [5]

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(b) If loads 'F1' and 'F2' are applied to **Sens1** and **Sens2** respectively, show that for all values of 'F1, F2' $\leq$ 200kN, the following relationships hold true:-

$$V_A = \left(\frac{R1+R2}{R1}\right).(2.5 \cdot F1 + 125) \cdot 10^{-3}$$ [3]

and

$$V_{out} = \left(\left(\left(\frac{R3+R4}{R3}\right).(2.0 \cdot F2 + 100)\right) - \left(\left(\frac{R1+R2}{R1}\right).(2.5 \cdot F1 + 125)\right)\right) \cdot 10^{-3}$$ [4]

c) If equal test loads from 0 – 250kN are applied to both Sens1 and Sens2 at the same time, draw a graph of the voltages you would expect to see at points 'A' and 'V_{out}' in figure Q1a. Label all the important points you observe on your graph and briefly explain their importance. [6]

d) During the installation of a new weighing machine, the input signals from **Sens1** and **Sens2** are reversed; the sensor that should have been connected to '$A1$' has been connected to the '$A2$' input while the sensor that should have been connected to '$A2$' has been connected to '$A1$'.

(i) During the testing procedure and using test loads of 0 - 300kN for both F1 and F2 simultaneously, the output results look very strange. Using the same procedure as described in part (c) above, draw a graph of the output voltages you would expect to see 'A' and 'V_{out}'. Carefully Label all the important points (including the point when V_{out} = 0V) you observe on your graph and briefly explain their relevance. [3]

(ii) Referring to your graph and the schematic in Figure Q1, explain the gradients of the different sections of the graph at 'V_{out}' and the fundamental causes. [4]

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Q2 The production of Ordinary Portland Cement (OPC) for making concrete relies on the use of a large rotary kiln that is used to heat raw materials to a very high temperature so the chemical reaction in producing OPC takes place correctly. During the production process, it is important that the raw ingredients are correctly distributed throughout the kiln and the method to do this is to regulate the supply of raw ingredients into the top of the kiln and/or to adjust the rotational speed of the kiln to distribute the ingredients. The kiln rotates on two large roller bearings and a load sensor on each set of rollers measures the weight producing an output voltage in proportion to that weight and is connected to a control board. A diagram of the rotary kiln is shown in Figure 2a.

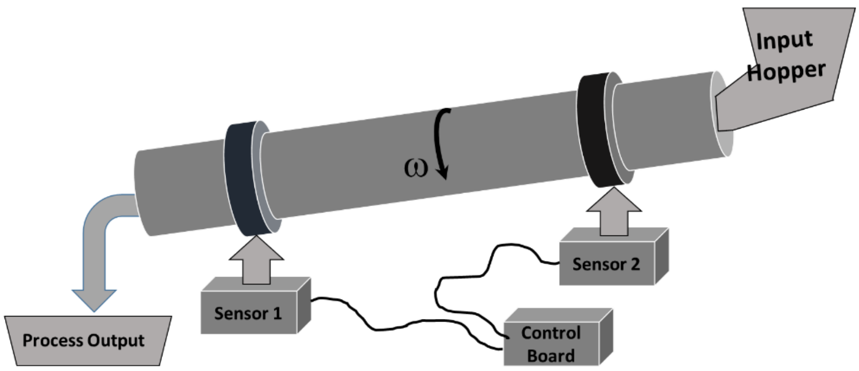

Figure Q2a: Diagrammatic representation of a rotary kiln

To optimise production efficiency, it is important that the weights detected by the sensors are accurate so a high quality, high accuracy amplifier circuit is used on the control board to amplify the signals received from the sensor circuits before being processed by a microcontroller. Figure Q2b shows one of the amplifier circuits used in the control board (the other is identical).

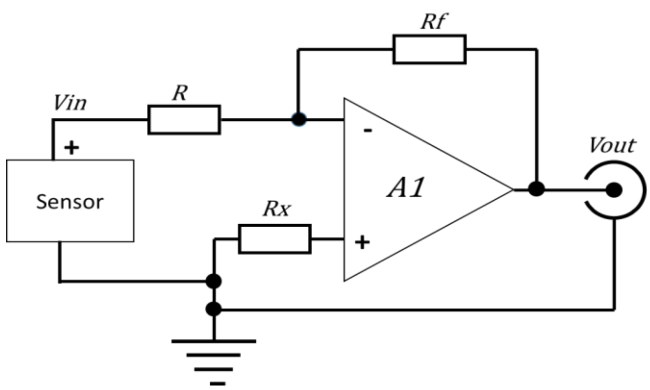

Figure Q2b: Control box sensor amplifier

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a) Redraw the circuit in figure Q2b showing all sources of DC error due to the OpAmp, A1. [5]

b) Hence derive an expression for the total DC error as a voltage referred to the output. Include the effects of both the bias and offset currents, and offset voltage and clearly state any assumptions you make. [8]

c) Using the expression you derived in (b), and if the resistor values for $R = 25k\Omega$ and $Rf = 750K\Omega$, choose a value for Rx which minimises the error voltage appearing at the output. [5]

d) Define a figure of merit (FoM) for the circuit shown in Figure Q2b. If the circuit is required to have an error at *Vout* of less than 50mV, use your FoM calculation to calculate the error at Vout for all 3 amplifiers. Hence, select the most suitable opamp for *A1* from Table Q2 and justify your choice [7]

Opamp	Offset Voltage (μV)	Bias current (pA)	Offset current (pA)	Price (RMB)
Amplifier A	440	10,000	7,500	10
Amplifier B	500	65,000	6,000	15
Amplifier C	100	85,000	20,000	12

Table Q2

Q3

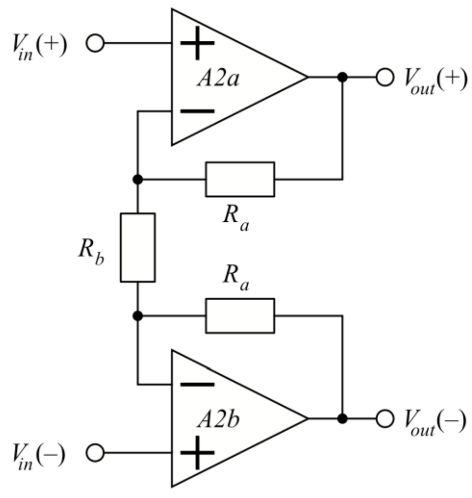

Figure Q3a

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a) Figure Q3a shows the circuit schematic of part of an instrumentation amplifier. Show that the expressions for the differential and common mode gains of the circuit in Figure Q3a are given by:

$$A_{Vdiff} = \frac{2.Ra+Rb}{Rb} \quad \text{and} \quad A_{CM} = 1 \qquad [5]$$

b) Including the circuit fragment shown in Figure Q3a, draw the diagram of a traditional three-opamp instrumentation amplifier. Write down expressions for the differential and common–mode gains of the complete circuit. [5]

Figure Q3b shows part of a schematic of an off-road electric e-bike. The 1000W wheel motor is driven from a 0 -> +48V variable voltage power supply and the current through the motor is monitored. This monitoring is important because if the wheel is subjected to excessive load or is prevented from turning (stalled), excess current will flow and damage both the motor and the Speed Controller. The current flowing through the motor is monitored using a series resistor '*RCM*' and an Instrumentation amplifier, *A1*. The voltage at *'Vout'* is proportional to the motor current and is used by the speed controller to control the drive power to the motor.

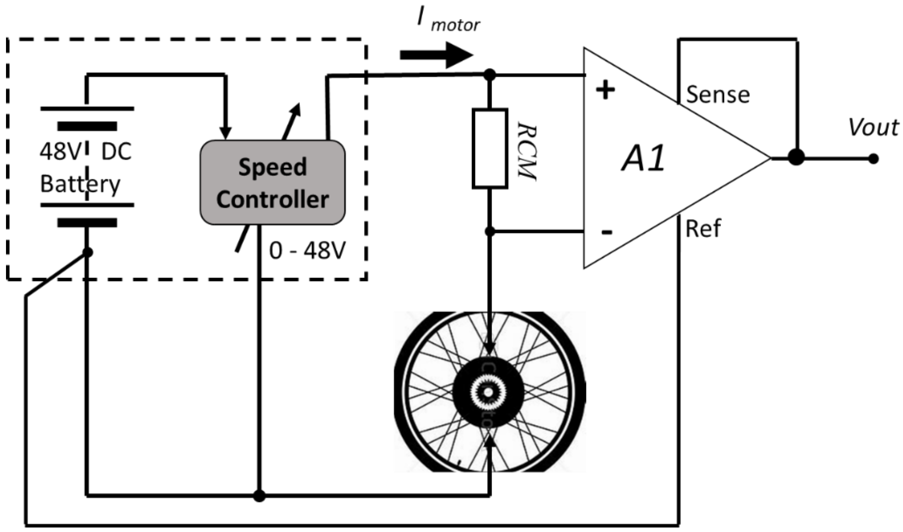

Figure Q3b: Simplified e-bike speed controller schematic

c) If the desired stall current through the motor is 25A and the maximum differential voltage applied to the instrumentation amplifier *'A1'* should be 200mV, show how you would calculate the correct value for *RCM* and determine that value. [3]

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d) The drive voltage for the motor can be from ‘0’ (off) to +48V (full power) and the motor current, I_{motor} can be from 0 - 25A. If RCM = 10mΩ, calculate the CMRR required for $A1$ if the drive current measurement error due to a common-mode signal must be less than 2%. [4]

e) Hence design $A1$ demonstrating the calculation of all resistance values and tolerances for an overall gain of x100. You can assume there are no restrictions on the power supplies for the amplifier. [5]

f) If the required gain tolerance is only +/- 5%, does this change the tolerance on any of the resistors? Justify your argument. [3]

Q4 In chemical processing it is very important to measure the temperature of fluids accurately. A common method of achieving this is to use a Platinum Thin Film temperature sensor that is placed into a probe into the liquid flowing in a specially modified pipe union that has the temperature sensor mounted in a sensor head onto the union (figure Q4a). One drawback of using these platinum sensors is their accuracy maybe affected by the length of connecting cable so it is common to mount the control circuitry and amplifier inside the sensor head. A typical circuit diagram is shown in figure Q4b.

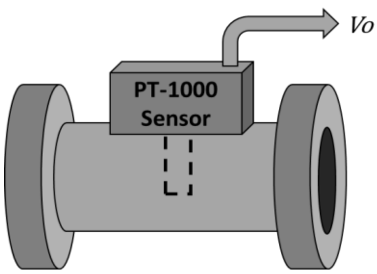

Figure Q4a: Pipe Union showing PT-1000 sensor arrangement

While the accuracy of the platinum thin film device is very predictable, it is not linear and a PT-1000 device responds to temperature according to the *Callendar-Van Dusen* equation:-

$$R_T = R_0(1 + 3.908 \cdot 10^{-3} \cdot T - 5.772 \cdot 10^{-7} \cdot T^2)$$

Where:-
R_T = resistance of the sensor at a given temperature (T)
R_0 = 1000 Ω measured at the reference temperature (0 °C)
T = Temperature in degrees Centigrade (°C)

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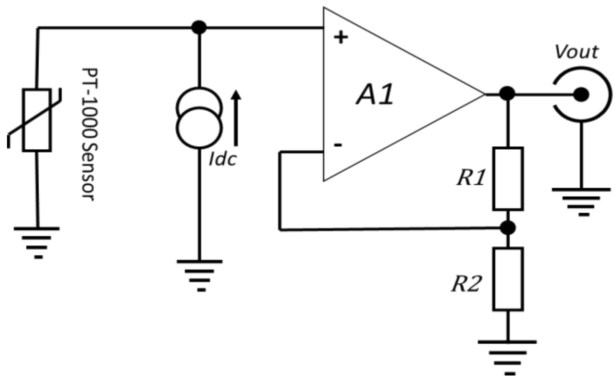

Figure Q4b: The control and amplifier circuitry in the Sensor head

a) Using the above information and assuming a reference current (*Idc*) =250uA, draw a table of the resistance of a single PT-1000 sensor for the temperatures 0, 50, 100, 250, 300 °C **and** the dc input signal this would generate at the input to amplifier *A1* [3]

b) Including any noise produced by *Idc* (but excluding shot noise), re-draw the circuit diagram showing all sources of noise. [5]

c) Hence derive an expression for the voltage noise spectral density present at the output (*Vout*) of the amplifier at a room temperature of 25 °C. Clearly identify each source of noise in your calculations and state any assumptions you make. [5]

d) The operational amplifier '*A1*' is one of the three shown in Table Q4b:

OpAmp	v_n **(nV /√Hz)**	i_n **(fA/√Hz)**
Amplifier A	1.3	1500
Amplifier B	12	25
Amplifier C	6.8	1200

Table Q4b

If R1 = 900Ω and R2 = 100Ω and without making detailed calculations, draw a table comparing the performance of each amplifier and identify which would to be most suitable for this application. Explain your reasoning using a suitable diagram. [6]

e) Using your amplifier choice from part (d), and assuming the temperature of the sensor and the circuit = 25 °C, R1 = 900Ω, R2 = 100Ω, and Idc = 250uA, what level of noise from Idc could be tolerated that would increase the overall noise appearing at the output (*Vout*) by +3dB? [6]

PHYSICAL CONSTANTS

Absolute zero should be assumed as -273.15 °C; Boltzmann Constant = 1.38 x 10^{-23} J.K^{-1}

End of question paper