ENGINEERING TRIPOS PART IIB

Monday 4 May 2009 2.30 to 4

Module 4B13

ELECTRONIC SENSORS AND INSTRUMENTATION

Answer not more than ***three*** *questions.*

All questions carry the same number of marks.

The ***approximate*** *percentage of marks allocated to each part of a question is indicated in the right margin.*

There are no attachments.

STATIONERY REQUIREMENTS	SPECIAL REQUIREMENTS
Single-sided script paper	Engineering Data Book
Graph paper	CUED approved calculator allowed

You may not start to read the questions printed on the subsequent pages of this question paper until instructed that you may do so by the Invigilator

1 A heating engineer is developing some devices to help assess the heat loss from houses by looking at the exterior surface temperatures of the roof, walls and windows. A pyrometer system is to be used using a 5 cm diameter polystyrene lens and a 5 mm diameter thermal detector, which comprises a silicon-based thermocouple with a thermal rating of 200 °C/W , placed 10 cm behind the lens.

(a) Calculate the temperature rise of the detector if the pyrometer is facing a brick wall at a temperature of 15 °C if the emissivity of the brick surface is 0.95 . If the silicon is doped to a resistivity of 10^{-3} Ωm, what is the magnitude of the raw signal from the detector ? [40%]

(b) In order to calibrate the sensing system, the engineer attaches a 100 Ω platinum resistance thermometer to the wall with a layer of adhesive. If the average thickness of the adhesive is 0.2 mm, what is the temperature error due to self-heating if the thermistor has an area of 10 mm^2 and is driven by a constant current of 10 mA ? The thermal properties of the various components are given below:-

Specific heat capacity of adhesive and thermistor = 1.2×10^3 J kg^{-1} K^{-1}
Thermal conductivity of adhesive = 0.35 W m^{-1} K^{-1} [25%]

(c) The engineer decides to investigate an alternative approach by exchanging the silicon thermocouple sensor for a semiconductor thermistor which has a resistance of 1 kΩ at 20 °C and β' = 3500 K, with otherwise similar physical properties to the original detector. What is the change in resistance of the thermistor as the pyrometer is moved from facing the brick wall to facing a window at 25 °C, with a surface emissivity of 0.85, assuming an ambient temperature within the pyrometer of 10 °C ? [35%]

State all assumptions and approximations made.

The Seebeck coefficient for silicon, $P_S = 2.6\, k \ln(\rho / 5\times10^{-6}) / q$ V K^{-1}

The Stephan-Boltzman constant, $\sigma_{SB} = 5.6 \times 10^{-8}$ W m^{-2} K^{-4}

2 (a) Explain the issues involved in the integration of Micro-Electro-Mechanical Systems (MEMS) with integrated circuits. Give an example of a MEMS-first process and illustrate by sketching representative process cross-sections as to how the integration with electronics is achieved. [30%]

(b) What is CMOS micromachining? What are its advantages and disadvantages? [20%]

(c) Explain the origin of thermo-mechanical noise. How does thermo-mechanical noise limit the resolution of MEMS accelerometers? [20%]

(d) A single-axis polysilicon surface micromachined accelerometer employs differential capacitive pick-off with 200 capacitive electrode pairs and operates in force-feedback mode. The out-of-plane thickness of the structural layer is $6\ \mu m$, the nominal gap between the electrodes is $1\ \mu m$ and the length of each electrode is approximately $400\ \mu m$. The proof mass weighs $1\ \mu g$ and the spring constant for motion along the sensitive axis is $1\ N\ m^{-1}$.

(i) Estimate the total capacitance between the fixed and movable electrodes.

(ii) Assuming half the capacitance is utilised for force-feedback and half the capacitance is utilised for sensing, calculate the voltage required to stabilise the proof mass and maintain a nominally stationary position for an applied acceleration of $50\ m\ s^{-2}$ along the sensitive axis. [30%]

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3 (a) Explain clearly but briefly the terms :-

Measurement Uncertainty, Systematic Uncertainty, Total Expanded Uncertainty. [30%]

(b) List and explain the steps that would be taken both before an item is sent for calibration and on its return. Assume that there are four similar instruments needing calibration but that only one is sent, to limit costs. [30%]

(c) Two new 1000 Ω temperature sensors, X, Y, have their resistances measured at 5 temperatures as shown in Table 1. As an added check on the ohmmeter, two standard 1000 Ω resistors, A, B, are measured too but they are kept in a constant temperature enclosure where the mean of their values is expected to be a constant 1001.1 Ω.

Temperature (°C)	X (Ω)	Y (Ω)	A (Ω)	B (Ω)
10	989.3	1019.3	989.8	1011.0
15	1007.8	1037.3	991.0	1012.4
20	1024.0	1053.6	989.8	1011.6
25	1042.1	1072.6	991.0	1012.2
30	1058.8	1090.8	990.4	1011.8

Table 1

Determine the meter error for each measurement temperature. Hence find the resistance values of the sensors, X and Y for the temperatures given.

By examining the differences for each 5 °C change determine a temperature coefficient in % per °C for X and Y and comment on the result.

What would you quote as the expanded measurement uncertainty for the ohmmeter using the coverage factor of 2 to provide a level of confidence of about 95% ? Express the result in % of the 1000 Ω nominal values here. [40%]

4 An ultrasonic detection system is being developed to monitor the build-up of limescale inside copper hot water pipes in an industrial plant. A pair of PZT transducers are clamped each side of the pipe and ultrasonic pulses are send across the pipe diameter. The PZT transducers operate at 1 MHz and have an electrical impedance of 100 Ω and an electro-mechanical conversion efficiency of 10% . See Table 2 for relevant properties.

(a) If the pipe external diameter is 40 mm and its wall thickness is 2 mm, how long does it take for an ultrasonic pulse to transit across the pipe when it is filled with water ? How does this compare to a pulse travelling around the pipe wall ? [15%]

(b) What amplitude of signal will be seen at the receiving transducer when the transmitting device is driven with a 12 V pulse, with the pipe conditions as follows:

(i) water filled with no limescale,
(ii) water filled with 5 mm of limescale on the walls ? [50%]

(c) It is planned to measure the flow velocity of water within the pipe by directing an ultrasonic beam at an angle of 30° to the pipe axis and using a Doppler detection circuit. Derive an expression for the Doppler frequency received as a function of volume flow rate of water in the pipe, assuming a 5 mm layer of limescale inside the pipe. [25%]

(d) What is likely to happen to the signals if the water has a large number of bubbles entrained within it ? [10%]

	Density ($kg\ m^{-3}$)	Speed of sound ($m\ s^{-1}$)	Attenuation ($dB\ m^{-1}$)
Air	1	340	1
Copper	8900	6000	8
Limescale	1500	800	50
Water	1000	1500	13
PZT	7500	4000	-

Table 2 Physical properties of materials

State all assumptions and approximations made.

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5 A new system to monitor vehicles passing along a road uses magnetic sensors to measure perturbations in the Earth's magnetic field as a vehicle passes. A variation of around 0.1% of the Earth's field is typically seen when a car passes within a few metres of a sensor.

(a) Briefly describe the principles of operation of the Hall effect and fluxgate magnetic sensing techniques. [25%]

(b) Design a fluxgate magnetometer system to produce a signal of around 1 V in amplitude in response to a passing car. Assume a gating frequency of 20 kHz and a magnetic core of diameter 1 mm and length 30 mm. [35%]

(c) An alternative approach is to attach a Hall effect sensing element to the end of a flux concentrating core. If the Hall element is 1 mm square with a thickness of 10 μm and the same core is used as in part (b), calculate the signal amplitude from a passing car when the Hall sensor is excited by a 5 V supply. The silicon has a *carrier mobility* of $0.14\ \text{m}^2\ \text{V}^{-1}\ \text{s}^{-1}$ and a *resistivity* of $0.045\ \Omega\ \text{m}$. [30%]

(d) Calculate the thermal noise voltage and equivalent magnetic noise signal of the Hall sensor, assuming a signal bandwidth of 100 Hz. [10%]

The Earth's magnetic field is approximately 45 μT in the UK.

The *demagnetising factor*, D, of a core of length, l, and diameter, d, is given by:
$D = (d/l)^2\ [\ \ln(2l/d) - 1]$

State all assumptions and approximations made.

END OF PAPER

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1.	(a)	0.09 °C, 1.07×10^{-4} V
	(b)	0.57 °C
	(c)	0.16 Ω
2.	(d)	2.12 pF, 217 mV
3.	(c)	X: 990.0, 1007.2, 1024.4, 1041.6, 1058.8; 0.344 ±0.008 %/°C Y: 1020.0, 1036.7, 1054.0, 1072.1, 1090.8; non-linear Expanded uncertainty approx. ± 0.06 %
4.	(a)	24.7 μs across diameter, 9.95 μs around wall
	(b)	(i) 110 mV into matched load or 220 mV open circuit (ii) 85 mV into matched load or 170 mV open circuit
	(c)	2174 Hz/(litre/sec)
5.	(b)	μ_{eff} = 291, eg. with 400 turns, G = 3000
	(c)	9.2 μV
	(d)	R = 4500 Ω, Vn = 85 nVrms, 0.42 nT with core or 120 nT without