EGT3
ENGINEERING TRIPOS PART IIB

Friday 30 April 2021   1:30 to 3:10

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.*

*Write your candidate number **not** your name on the cover sheet and at the top of each answer sheet.*

STATIONERY REQUIREMENTS
Write on single-sided paper.

SPECIAL REQUIREMENTS TO BE SUPPLIED FOR THIS EXAM
CUED approved calculator allowed.
You are allowed access to the electronic version of the Engineering Data Books.

10 minutes reading time is allowed for this paper at the start of the exam.

The time taken for scanning/uploading answers is 15 minutes.

Your script is to be uploaded as a single consolidated pdf containing all answers.

1 An ultrasonic testing system is being used on composite resin roof panels to check that the resin has properly set hard. The panels are 50 mm thick and a pair of 1 MHz transducers are clamped on each side of the panel, with a 2 mm thick silicone rubber coupling layer sandwiched at each surface. The ultrasonic transducers are made from PZT and have the following properties: diameter = 10 mm, electrical impedance = 250 Ω, electro-mechanical efficiency = 25 % , full beam angle = 20 º.

The physical properties of various materials are given in table 1 below.

(a) What is the change in pulse transit time across the panels as the resin hardens from partly set to fully set ? [10%]

(b) If the transmitting transducer is driven with a signal of amplitude 20 V, what is the open-circuit voltage of the signal produced by the receiving transducer when:

(i) the resin is partly set,

(ii) the resin is fully set ? [50%]

(c) When installed on a building, the panels are held in place by stainless-steel strips of length 120 mm, width 20 mm and thickness 3 mm. The strips are firmly clamped at each end to prevent rotation and carry a pair of strain gauges on the upper and lower surfaces, 30 mm along from one end, to monitor roof loads with a full-bridge arrangement. If the strain gauges have a gauge factor = 2 and are powered by a 10 V supply, what is the raw signal the bridge produces when the strip is loaded to 200 N ? How far will the beam end deflect under this load ? Assume Young's modulus for stainless steel = 200 GN m^{-2}. [40%]

State all assumptions and approximations made.

Table 1: Physical properties of materials

	Density (kg m^{-3})	Speed of sound (m s^{-1})	Attenuation (dB m^{-1})
Air	1	340	3.2
Resin (partly set)	900	1300	25
Resin (fully set)	900	1600	18
Silicone rubber	1200	1800	7
PZT	7500	4000	-

2 A portable laser scanner for a graphics light show uses a 2 mm long cantilever of width 100 µm, with a 1 mm × 1 mm mirror on the end, to deflect the laser beam as it tilts. The mirror and cantilever are fabricated from a silicon crystal wafer slice of thickness 25 µm. The mirror is deflected by means of a fixed metal film capacitor plate situated directly beneath it on a slice of glass, such that a voltage can be applied across the 25 µm air gap between the plate and mirror.

(a) Briefly describe the physical and chemical processes used to micro-fabricate the structure described above. [25%]

(b) What is the capacitance between the mirror and plate, with zero voltage applied ? Note: the permittivity of free space, $\varepsilon_0 = 8.854 \times 10^{-12}$ F m^{-1}. [10%]

(c) Calculate the spring constant for the cantilever and hence estimate the mechanical resonant frequency of the structure. Assume the following values for the physical properties of silicon: density = 2330 kg m^{-3}, Young's modulus = 110 GN m^{-2}. [25%]

(d) Derive an estimate of the plate-mirror capacitance when the mirror has been tilted down by an angle of 0.5° and hence calculate the voltage which must be applied across the deflection capacitance to produce this tilt angle. [25%]

(e) Suggest how the laser beam deflection could be accurately controlled via feedback and describe the advantages of closed-loop operation. [15%]

State all assumptions and approximations made.

3 (a) A 3-D laser scanner is being designed to map the inside of caves using optical range-finding with pulsed time-of-flight. The laser has a power of 10 mW at 650 nm and the detection system uses a 20 mm diameter collection lens and a photo-diode with a quantum efficiency of 80 %. The ranging distance varies from 1 m to 50 m and the cave walls may be considered to back-scatter light isotropically with a reflectance range of 10 % to 50 %.

Note: the energy of a photon = $h\,c\,/\,\lambda$ where Planck's Constant, $h = 6.626 \times 10^{-34}$ J s.

(i) Calculate the maximum and minimum pulse flight times for the conditions given above. [10%]

(ii) What are the maximum and minimum values of photo-current expected ? [20%]

(iii) A transimpedance amplifier circuit is used to amplify the photo-current using a 100 kΩ resistor in parallel with a 10 pF capacitance in the feedback path. If the amplifier has an input noise current density of 1.4 pA $\text{Hz}^{-0.5}$, estimate the minimum signal-to-noise ratio expected before any pulse averaging is used. [20%]

(b) A pyrometer system is also being employed to monitor the temperature of the cave walls for diagnosing possible geothermal activity. The pyrometer uses a 1 mm diameter HgCdTe photo-diode with a responsivity of 0.15 A W^{-1}, placed 50 mm behind a 20 mm diameter ZnSe lens. The cave surface typically has an emissivity of 0.90 .

Note: Lambert's Law, $\delta W = W \cos\theta\, A\, \delta\omega\, /\, \pi$ and Stephan's Law, $W = \varepsilon\, \sigma_{SB}\, T^4$ where the Stefan-Boltzmann Constant, $\sigma_{SB} = 5.67 \times 10^{-8}$ J K^{-4} m^{-2} s^{-1}.

(i) What is the photo-current detected when the pyrometer is viewing a surface temperature of 30 °C ? [20%]

(ii) The HgCdTe photo-detector is very expensive, what other detector technologies could be considered as alternatives ? [15%]

(c) Show how two pairs of bipolar transistors can be configured to form a temperature sensor circuit with an output voltage proportional to absolute temperature, with a scale factor of 0.1 mV K^{-1}. [15%]

State all assumptions and approximations made.

4 Formula-E racing cars employ a battery pack with a voltage up to 1000 V and a current up to 300 A when racing. The high voltage system is electrically insulated from the car chassis for safety; consequently, isolated sensors are needed to measure line current and voltage. A system is being designed which uses a pair of identical toroidal cores to monitor current and voltage separately: each core has a Hall effect sensor fitted in its air gap. The cores have a *relative permeability,* μ_r, of 2000, a magnetic circuit length of 80 mm, a cross-section of 75 mm^2 and a 0.5 mm air gap. The Hall sensors are made from a 200 μm square slice of silicon with a thickness of 10 μm, doped to a resistivity of 10^{-3} Ω m and supplied by 5 V d.c..

(a) For the current sensor, the power cable is fed through the centre of the toroid core, effectively as a single turn.

(i) What is the magnetic flux density across the Hall sensor when the car draws full power ? [15%]

(ii) Derive the responsivity of the Hall sensor element and hence calculate the Hall output voltage signal for the car at full power, assuming the carrier mobility in silicon to be $0.16\ \text{m}^2\ \text{V}^{-1}\ \text{s}^{-1}$. [20%]

(b) The voltage sensor operates by monitoring the current drawn through a 100 kΩ resistor, connected across the battery terminals and in series with 800 turns of wire wound around the other toroid core.

(i) What is the inductance of the voltage sensor, appearing in series with the resistor ? [20%]

(ii) What is the Hall sensor output signal when the voltage is 850 V ? [15%]

(iii) Derive the bandwidth of the Hall sensor. How does this limit the bandwidth of measureable voltage variations ? [30%]

Note: Einstein's relation for the diffusion coefficient, $D = \mu k T / q$

State all assumptions and approximations made.

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4B13 2021 Numerical answers

1(a) 7.2 μs

1(b)(i) 1.42 V amplitude, open cct.

1(b)(ii) 1.56 V amplitude, open cct.

1(c) 0.02 V, 3.2 mm

2(b) 0.354 pF

2(c) k = 5.33 N/m, 1522 Hz

2(d) 0.98 pF, 40.2 V

3(a)(i) 6.67 ns, 333 ns

3(a)(ii) 104 nA max., 8.36 pA min.

3(a)(iii) S/N = 0.014, very low – hence pulse averaging needed

3(b)(i) 2.03 μA

3(c) r = 3.188 (area ratio)

4(a)(i) 0.698 T

4(a)(ii) 0.8 V/T, 0.558 V

4(b)(i) 0.112 H

4(b)(ii) 12.7 mV, t_{Hall} = 2.66 μs, 132 kHz but L/R = 1.12 μs, so overall: t ~ 3.6 μs, 90 kHz