Version PAR/3

EGT3
ENGINEERING TRIPOS PART IIB

Tuesday 6 May 2014 2 to 3.30

Module 4B13

ELECTRONIC SENSORS & 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.*

STATIONERY REQUIREMENTS
Single-sided script paper

SPECIAL REQUIREMENTS TO BE SUPPLIED FOR THIS EXAM
CUED approved calculator allowed
Engineering Data Book

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

1 (a) A row of semiconductor thermistors is used in an industrial drying oven to monitor the temperature in different zones. The thermistors have the following properties: R = 200 Ω nominal at 0 °C, with a β' value of 3200 ± 100 due to manufacturing tolerances, and are powered by a 5 mA constant current source.

Derive the nominal output voltage signal for an oven temperature of 60 °C and determine the variation in oven zone temperatures likely due to the tolerance in the thermistor properties. [25%]

(b) The heater element in a pharmaceutical pouch sealer is rapidly temperature cycled between 50 °C and 150 °C, whilst melting the plastic seam closed and cooling to release the sealed pouch. The heater element has a small platinum resistance thermometer attached to its surface to monitor the sealing process. The thermometer element has the following properties:

nominal resistance:	100 Ω at 25 °C	mass:	0.05 g
temperature coefficient:	0.385 Ω K^{-1}	area:	10 mm^2
adhesive thickness:	0.1 mm		
specific heat capacity:	1.2 J g^{-1} K^{-1}		
thermal conductivity:	0.25 W K^{-1} m^{-1}		

(i) Calculate the thermal time constant of the thermometer element and hence estimate the maximum temperature cycling frequency which the sensor could monitor. [30%]

(ii) If the sensing resistance is powered by a constant current of 10 mA, estimate the temperature measurement error induced by self heating of the device. [15%]

(c) A pyrometer system monitors the surface temperature of welded pouch seams, as they pass along a production line. The nominal temperature expected is 100 °C and the emissivity of the pouch surface is 0.90. If the pyrometer system comprises a 3 mm diameter pyroelectric detector placed 50 mm behind a ZnSe lens of 30 mm diameter, calculate the electrical signal amplitude expected from the sensor element if it has a thermal rating of 200 °C W^{-1} and a pyroelectric response of 50 mV K^{-1}. [30%]

Note: The Stephan – Boltzmann constant, $\sigma_{SB} = 5.67 \times 10^{-8}$ W m^{-2} K^{-4}

2 (a) Describe the types of structure and process steps utilized for the fabrication of MEMS gyroscopes based on a silicon substrate. Explain how the resonant structures and clearances between components are defined, and briefly describe how the device operates and how its output signals are derived. [35%]

(b) A magnetic microscope system comprises a cantilever beam micro-machined in silicon, tipped with a thin magnetic coating at its free end. The silicon cantilever beam is 1.5 mm long, 150 μm wide and 5 μm deep. A half bridge of strain gauges is diffused into the beam at its root such that a signal is produced when the free end is attracted towards magnetized zones in an object, such as a hard disc platter, scanned beneath the cantilever.

(i) If the strain gauges have a *Gauge Factor* of 200 and are powered from a ± 2.5 V supply, calculate the raw signal from the system when the tip force is 100 pN. [30%]

(ii) Estimate the resonant frequency of the cantilever beam and determine the amplitude of tip vibration expected if the device were positioned over a current-carrying track which induced an alternating force of 100 pN on the tip, assuming a resonance *Q-factor* of 80 . [15%]

(iii) The a.c. signal from the strain gauges, which have a resistance of 10 kΩ each, is amplified by an operational amplifier using a feedback resistance of 10 MΩ . The operational amplifier has an input noise voltage density of 5 nV $Hz^{-0.5}$ and an input noise current density of 10 pA $Hz^{-0.5}$. Calculate the rms noise voltage expected at the output, over a bandwidth up to the resonant frequency of the beam. You may neglect any shot noise or flicker noise. [20%]

State all assumptions and approximations made.

3 An interplanetary space probe is being sent to Mercury to measure its magnetic field. Current estimates for the expected magnetic flux density are around 500 nT and a single-core fluxgate magnetometer system is being developed for the mission.

(a) Draw a schematic block diagram of the functional components of a fluxgate magnetometer system, which produces an analogue d.c. voltage proportional to the magnetic flux density detected. [25%]

(b) Given a high permeability magnetic core of length, ℓ, and diameter, d, wound with a pick-up coil comprising N turns of wire, derive an expression for the magnitude of the d.c. signal voltage produced when the sensor experiences a magnetic flux density of B T, when the core is excited with a drive frequency of f Hz. [25%]

(c) If the sensor magnetic core is 30 mm long with a diameter of 0.2 mm and is wound with 600 turns , estimate the self-inductance of the device. Hence calculate the capacitance which should be connected across the coil to maximize the system sensitivity if the drive frequency used is 30 kHz. [35%]

(d) Calculate the magnitude of the analogue output signal expected as the probe passes Mercury, if the resistance of the coil in part (c) is $16\ \Omega$, and the capacitor can be considered lossless. [15%]

State all assumptions and approximations made.

Note: The demagnetizing factor, D, of a high permeability core of length, ℓ, and diameter, d, may be approximated by: $D = (d / \ell)^2\ [\ln (2\ell / d) - 1]$

4 A team of coastal surveyors is developing some ultrasonic and optical equipment to map the geometry of the cliffs and sea bed, in order to monitor coastal erosion.

(a) The depth of the water is measured with an ultrasonic pulse-echo system, in which a 5 cm diameter PZT transducer with an electrical impedance of 250 Ω is driven with 120 V pulses. The ultrasonic pulses are transmitted down from the surface and reflected back from the sea bed to the same transducer, which then produces an electrical signal from the echo.

What is the pulse-echo delay time when the water is 10 m deep ? What is the open-circuit magnitude of the raw echo pulse from the transducer if it has an electro-mechanical conversion efficiency of 10 % , and the sea bed has a reflectivity of 20 % ? [40%]

(b) The shape of the cliffs is determined with a scanned laser system, where the pulse-echo transit time of optical pulses is measured as the beam is scanned across the cliff face. The laser has a pulse power of 50 mW and the back-scattered optical pulse is collected by a lens of diameter 50 mm and focused onto a photo-diode with a responsivity of 0.7 A/W at the operating wavelength of 780 nm.

(i) What is the amplitude of the detected photo-current when measuring a distance of 50 m , assuming a Lambertian reflectivity of 15 % for the cliff surface and a clear day, i.e. with no optical attenuation ? [15%]

(ii) What is the quantum efficiency of the photo-diode used ? Given that the minimum detectable optical power of the photo-diode is 4×10^{-14} W $Hz^{-0.5}$, and this limits the range of the system, estimate the maximum range which can be measured at 100 readings per second, both on a clear day, and when the optical attenuation is 3 dB km^{-1} . [45%]

	Density ($kg\ m^{-3}$)	Speed of sound ($m\ s^{-1}$)	Ultrasonic attenuation ($dB\ m^{-1}$)
Sea water	1050	1550	1.5
PZT	7500	4000	-

Physical properties of materials

END OF PAPER

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4B13 2014 – Numerical answers

1 (a) 0.121 V, +/- 10.3 K
(b) 2.4 s, 0.066 Hz
(c) 0.62 mW IR, 6.2 mV

2 (b)(i) $dR/R = 3.2 \times 10^{-7}$, 0.8 μV
(b)(ii) 38.5 nm
(b)(iii) 1.07 mV

3 (c) 2.27 mH, 3.10 nF
(d) Q = 53.5, 0.289 V

4 (a) 58.8 μV matched load, 0.118 mV open cct.
(b)(i) 1.31 nA
(b)(ii) q.e. = 111 % (photo-diode can have gain)
clear range 3.42 km, atten. (by iteration) 1.35 km