ENGINEERING TRIPOS PART IIB

Monday 23 April 2012 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
Single-sided script paper
Graph paper

SPECIAL REQUIREMENTS
Engineering Data Book
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) The temperature of the battery pack in an electric motorcycle is monitored with a semiconductor thermistor, connected into a potential divider circuit with a 1 kΩ resistor and powered from a 5 V d.c. supply. If the thermistor has a resistance of 1 kΩ at 20 °C and a β' value of 3300, what is the output voltage from the circuit at 55 °C ? [20%]

(b) Describe how an array of 4 bipolar transistors can be configured to produce a temperature sensor with an output voltage directly proportional to absolute temperature. Over what temperature measurement range would this technique be suitable ? [20%]

(c) A passive infra-red movement detector comprises a pyroelectric detector of diameter 5 mm situated 25 mm behind a polystyrene lens of diameter 30 mm. Estimate the infra-red power falling on the detector when a person walks into view nearby, assuming that people have an emissivity of 0.90 and a surface temperature of 35 °C. [30%]

(d) A single metal strain gauge is bonded to the surface of a beam with adhesive in order to monitor the stress in that component, which forms part of a factory building. The strain gauge has a resistance of 120 Ω with a temperature coefficient of 0.1 % per °C and is supplied with a constant current of 10 mA. If the average thickness of the adhesive is 0.1 mm, what is the strain error introduced by self-heating if the strain gauge has an area of 5 mm^2 ? [30%]

State all assumptions and approximations made.

Thermal conductivity of adhesive = 0.25 $W\ m^{-1}\ K^{-1}$

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

2 (a) Describe the types of structure and process steps utilized for the fabrication of MEMs pressure and acceleration sensors based on a silicon substrate. What techniques are employed to create readout signals from these devices ? [40%]

(b) A fibre-optic switch comprises a silicon cantilever beam with a thin, flexible optical fibre bonded to its top surface such that the end face of the fibre directly aligns, across a small air gap, with that of another optical fibre fixed to the substrate. To break the optical path, a fixed capacitor plate situated 5 μm beneath the underside of the cantilever deflects the beam down when a voltage is applied, so misaligning the optical fibre faces.

Each optical fibre core diameter is 2 μm, and the cantilever beam is 1 mm long with a width of 15 μm and a depth of 5 μm. The deflection plate is 15 μm × 15 μm and is situated under the free end of the beam.

(i) What is the initial capacitance between the deflection plate and the beam, before the switch is activated ?

(ii) What voltage must be applied to the deflection plate in order to break the optical path ? [40%]

(c) Estimate the resonant frequency of the cantilever and hence determine the settling time after switching, assuming the configuration to have a resonant *Q-factor* of 50. [20%]

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3 An optical velocity measurement system to monitor the closing speed of a spacecraft approaching a satellite uses a collimated 500 mW, 635 nm laser beam with amplitude modulation at 120 MHz. Back-scattered light from a satellite is collected by a lens of diameter 10 cm and focused on to a photodiode with a responsivity of 0.36 A W^{-1}. The photodiode signal is amplified and mixed with a reference signal from the laser drive oscillator to produce a Doppler frequency signal.

(a) What is the magnitude of the received optical signal from a satellite at a range of 1 km if the satellite back-scatters the light isotropically into a hemisphere ? [25%]

(b) If the closing speed is 50 m s^{-1}, what is the Doppler frequency produced by the system ? [15%]

(c) If the system has to be able to measure closing speeds up to 500 m s^{-1} and the photodiode transimpedance amplifier has a noise current density of 0.06 pA $\sqrt{Hz^{-1}}$, a noise voltage density of 1.5 nV $\sqrt{Hz^{-1}}$ and is used with a feedback resistor of 10 kΩ, estimate the signal to noise ratio for the conditions described in part (a). [35%]

(d) What is the quantum efficiency of the photodiode in this application ? [10%]

(e) How could the system be adapted to measure range as well as velocity and what precautions should be taken to avoid ranging ambiguity ? [15%]

4 An industrial load cell used to weigh vehicles comprises a steel toroid ring of rectangular section with an internal diameter of 100 mm, an external diameter of 110 mm and a thickness of 20 mm, with an air gap of 1 mm cut across one side. The compressive load is applied across the ring diameter, so as to close the air gap by 0.1 mm for each 100 N of applied force. The toroid is wound with a coil of 500 turns to form a variable inductor.

(a) If the relative permeability, μ_r, of the steel is 1500, calculate the inductance of the load cell under zero load conditions, and when a force of 500 N is applied. [25%]

(b) What is the magnetic flux density in the air gap when a current of 1 A is passed through the coil, under zero load and with 500 N applied ? [15%]

(c) An alternative readout scheme is to place a Hall effect sensor in the air gap whilst driving the coil with an excitation current. The Hall sensor comprises a slice of silicon with lateral dimensions 0.5 mm × 0.5 mm and a thickness of 10 μm, doped to a resistivity of 0.02 Ω m and supplied with a voltage of 5 V. What is the change in output signal when a load of 500 N is applied if the coil current is 1 A ? [35%]

(d) Estimate the error in the load cell reading due to the magnetic force produced across the air gap by the coil current of 1 A. [25%]

The mobility of silicon is 0.15 $m^2 V^{-1} s^{-1}$

State all assumptions and approximations made.

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5 An anti-theft system in a designer clothes store uses a tag, which is attached to the garments, and a detection system near the door. The tag comprises an induction coil connected to a 40 kHz ultrasonic transmitter. A large coil, which emits a 40 kHz alternating magnetic field, is placed near the door alongside an ultrasonic receiving transducer. If a tag should appear in proximity to the coil, it will emit ultrasound which will be detected by the receiver.

(a) If the magnetic field has a flux density of 1 mT in the doorway, what voltage would be induced in the tag coil if it comprises a 4 cm diameter coil of 200 turns of wire? [15%]

(b) If the ultrasonic transducers have an isotropic beam profile, an electrical impedance of 5 kΩ, an acoustic impedance of 10^5 kg m^{-2} s^{-1} and an electro-mechanical conversion efficiency of 15 %, what is the ultrasonic intensity 2 m away from a tag if it is driven by the coil in part (a) ? [35%]

(c) A similar ultrasonic transducer is used as a receiver to detect any emitted ultrasound. If it has a diameter of 4 cm, what open-circuit signal voltage does it produce when 2 m away from the transmitting tag in part (b) ? [30%]

(d) If instead of an isotropic beam profile the transducers have a Lambertian beam profile, what effect would this have on the received signal magnitudes and the overall performance of the system ? [20%]

Physical properties of air

	Density (kg m^{-3})	Speed of sound (m s^{-1})	Attenuation (dB m^{-1})
Air	1.2	340	2

State all assumptions and approximations made.

END OF PAPER

4B13 2012 Numerical Answers

1(a) 1.16 V
(b) $V_o = (kT \ln r)/q$
(c) 3.2 mV
(d) 0.048 % strain

2(b) 58.5 V
(c) 0.27 ms

3(a) 225 pA
(b) 40 Hz
(c) ~ 8.7
(d) 0.71

4(a) 0.0257 H @ 0 N, 0.0435 H @ 500 N
(b) 0.515 T @ 0 N, 0.873 T @ 500 N
(c) 0.269 V
(d) ~ 10-15 N

5(a) 44.6 V rms
(b) 7.64×10^{-6} W m^{-2}
(c) ~ 2 mV pp