Version PAR/2

EGT3
ENGINEERING TRIPOS PART IIB

Thursday 4 May 2023 14:00 to 15.40

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.*

STATIONERY REQUIREMENTS
Single-sided script paper

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

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

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

You may not remove any stationery from the Examination Room.

1 A mechanism on the back of a lorry to lift waste bins includes a load cell to measure the weight of the bins being emptied. The load cell comprises a steel toroid ring with a relative permeability, μ_r, of 2500. It has a rectangular cross-section with an internal diameter of 50 mm, an external diameter of 60 mm and a thickness of 10 mm, with an air gap of 0.5 mm cut across one side. The tensile load is applied across the ring diameter, so as to open the air gap by 0.1 mm for each 1000 N of applied force. The toroid is wound with a coil of 250 turns to form a variable inductor.

(a) Calculate the change in inductance of the load cell when a tensile force of 1000 N is applied to it. [25%]

(b) What is the change in magnetic flux density within the air gap when the load changes from zero to 1000 N, given a current of 1 A through the coil windings ? [15%]

(c) Estimate the magnetic force produced across the air gap when the coil carries a current of 1 A and hence comment on the feasibility of using a current force feedback system to maintain the inductance at a constant value when a load is applied. [25%]

(d) 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 GaAs with lateral dimensions 0.25 mm × 0.25 mm and a thickness of 10 μm, doped to a resistivity of 0.05 Ω m and supplied with a current of 5 mA. What is the change in output signal when a load of 1000 N is applied if the coil current is 1 A, and what is the response time of the Hall sensor ? [35%]

The mobility of GaAs is $0.90\ \mathrm{m^2\,V^{-1}\,s^{-1}}$.

State all assumptions and approximations made.

2 A virtual-reality movement tracking system employs pairs of ultrasonic and optical transducers to measure distances to certain points on the user. Strings of pulses at around 500 kHz are simultaneously transmitted from an LED and ultrasonic transducer pair so that the difference in time-of-flight between the optical and ultrasonic signals can be used to infer the distance to a fixed receiver. The LEDs and ultrasonic devices both have isotropic radiation patterns over a hemisphere forward of the devices.

(a) What is the flight-time difference between the optical and ultrasonic signals at a range of 5 m ? [10%]

(b) If the ultrasonic transducers are 15 mm diameter, made from PZT and have an electrical impedance of 500 Ω, an electro-mechanical efficiency of 20% and a matching cone to reduce the acoustic impedance by a factor of 500, what is the ultrasonic power density at a range of 5 m when the transducer is driven with 15 V pulses, and what open-circuit electrical signal is produced by a receiving transducer of the same type ? [30%]

(c) The LED is driven by 100 mA pulses, has a radiant power of 0.20 W A^{-1} and a wavelength of 780 nm. If the optical signals are detected by a 5 mm^2 area photo-diode with a quantum efficiency of 65%, what is the magnitude of the photo-current produced when operating at a range of 5 m ? [25%]

(d) How do the magnitudes of the electrical signals from the optical and ultrasonic systems change when the range is reduced from 5 m to 2 m ? [15%]

(e) Draw a schematic block diagram of the system architecture, showing the key functions required to produce range signals from each optical / ultrasonic pair, given that multiple pairs are driven with pulse frequencies around 10 kHz apart. [20%]

Table of physical properties

	Density (kg m^{-3})	Speed of sound (m s^{-1})	Attenuation (dB m^{-1})
Air	1.22	340	1.2
PZT	7500	4000	-

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3 Cat food is packaged in pouches on a production line which fills and heat-seals the pouch ends before passing them through a steam oven to sterilise the contents, enabling a long shelf life. The heat-sealing process uses resistive bar elements, through which a large current is passed to heat them up, and they are then pressure clamped each side of the pouch ends. To monitor the sterilisation process, a pyrometer measures the surface temperature of the pouches as they exit the oven on a conveyor belt.

(a) The heat-sealing element temperature is monitored with a Ni foil resistance thermometer bonded to the heating bar, where the thermometer element and adhesive layer have the following properties:

nominal resistance: 120 Ω at 25 °C	mass: 0.025 g
specific heat capacity: 1.2 J g^{-1} K^{-1}	area: 5 mm^2
adhesive thickness: 50 μm	thermal conductivity: 0.30 W K^{-1} m^{-1}

(i) Calculate the thermal time constant of the thermometer element and hence estimate the 10% - 90% rise time of the sensor. [25%]

(ii) If the sensing resistor is connected into a half-bridge circuit with a matched resistor and powered by a 5 V supply, estimate the self-heating temperature error. [20%]

(b) The Ni foil sensor is connected into a bridge with 3 matching fixed resistors, where the bridge signal is amplified by an operational amplifier connected as a differential amplifier using a feedback resistance of 1 MΩ in parallel with a 1 nF capacitor. The operational amplifier has an input noise voltage density of 3 nV $Hz^{-0.5}$ and an input noise current density of 5 pA $Hz^{-0.5}$. Calculate the rms noise voltage expected at the output and calculate the amplified output responsivity if the Ni foil sensor has a temperature coefficient of 0.90 Ω K^{-1}. [20%]

(c) The pouch surface pyrometer system alternately measures the pouches at 90 °C and the conveyor belt gaps at 30 °C, where both surfaces have an emissivity of 0.95. If the pyrometer system comprises a 2 mm diameter pyroelectric detector placed 40 mm behind a ZnSe lens of 20 mm diameter, calculate the electrical signal amplitude expected from the sensor element if it has a thermal rating of 250 °C W^{-1} and a pyroelectric response of 50 mV K^{-1}. [35%]

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

4 (a) Describe the process steps utilized for the fabrication of surface micro-machined devices such as cantilever beams on a planar substrate, explaining how the structures and clearances between components are defined. [30%]

(b) A miniature gas flow sensor comprises a silicon cantilever beam with a 50 µm diameter gas nozzle directed downwards above the free end, such that the dynamic pressure of the flowing gas jet ($p = ½\rho v^2$) creates a force which deflects the beam tip. The cantilever beam is 500 µm long, 75 µm wide and 2 µm deep. A full-bridge of strain gauges is diffused into the beam at its root, such that a signal is produced when the end is deflected. A square capacitor electrode, measuring 75 µm per side, is arranged underneath the free end of the beam, with a 2 µm air gap, so that a self-test/calibration function can be activated when required.

(i) Calculate the maximum air volume flow rate which could be measured by the sensor before the air gap is closed by the beam deflection. [15%]

(ii) If the strain gauges have a *Gauge Factor* of 200 and are powered from a 5 V supply, calculate the raw signal from the sensor when the air flow is half the maximum value measurable. [15%]

(iii) Estimate the resonant frequency of the cantilever beam and determine the response time of the flow sensor, assuming a resonance Q-factor of 60. [20%]

(iv) What voltage should be applied to the test electrode in order to replicate a beam tip deflection equivalent to half the maximum measurable flow rate ? [20%]

State all assumptions and approximations made.

END OF PAPER

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