EGT3
ENGINEERING TRIPOS PART IIB

Monday 22nd April 2024 9:30 to 11.10

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.*

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 current transducer has a miniature fluxgate sensor within the air-gap of a ferrite toroid ring, and also, a 100-turn coil is wound around the toroid, where the conductor being monitored passes through the toroid centre. The toroid material has a relative permeability, μ_r, of 5000 with a saturation flux density of 0.5 T. It has a rectangular cross-section with an internal diameter of 15 mm, an external diameter of 25 mm and a thickness of 8 mm, with an air-gap of width 500 μm cut across one side.

(a) Calculate the self-inductance of the toroid coil winding, and the magnetic flux density in the air gap when the central conductor carries 5 A d.c. Hence estimate the conductor current required to cause the onset of saturation in the ferrite material. [20%]

(b) What is the open-circuit output voltage induced across the toroid coil when the conductor carries 5 A a.c. at 1 kHz? [10%]

(c) What output voltage is produced across the toroid coil when it is loaded with a 1 Ω resistance whilst the conductor carries 5 A a.c. at 1 kHz, and what is the minimum frequency at which this a.c. current transformer can operate effectively? [15%]

(d) The fluxgate sensor comprises a pair of micro-fabricated cores wound with a 200-turn pick-up coil. The cores are each 450 μm long, with a diameter of 25 μm, and are excited into alternating saturation with a drive frequency of 10 MHz. Derive the responsivity of the fluxgate sensor and hence calculate the value of the raw demodulated fluxgate sensor signal when the central conductor carries 5 A d.c., assuming no amplification has been applied to the signal. [20%]

(e) Draw a schematic diagram of the fluxgate interface circuitry and indicate how this could be connected to the toroid coil, forming a closed-loop feedback system, in order to maintain near-zero flux across the toroid air-gap and produce an output signal voltage proportional to the conductor current. What are the advantages of this configuration? [20%]

(f) Calculate the total voltage gain required in the feedback drive amplifiers if the system in part (e) is to null the air-gap flux to less than 0.1% of its open-loop value for a given central conductor current, given a 1 Ω resistance in series with the toroid coil. [15%]

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.

2 An industrial processing tank, 120 cm tall, contains liquid sulphuric acid, sometimes covered by a layer of foam which scatters ultrasound, through its bulk or from its surface, with a Lambertian distribution. The walls of the tank are made from 10 mm thick PTFE and a PZT ultrasonic transducer is directly bonded to the outside of the base of the tank pointing upwards, whilst a facing transducer, with a matching cone to reduce its acoustic impedance by a factor of 750, is fixed inside the top of the tank in the air-space, pointing directly down.

(a) What are the pulse-echo and direct flight-times between the transducers when the tank is half full of liquid, with no foam layer and ignoring multiple reflections? [15%]

(b) The ultrasonic transducers are 10 mm diameter, with an electrical impedance of 200 Ω, an electro-mechanical efficiency of 15 % and a beam angle of ± 5°. If the base transducer is driven with 25 V pulses, what open-circuit electrical signal is produced by the same transducer from the liquid surface echo, and what signal is produced by the air-space transducer from the directly received pulse, assuming no foam layer? [30%]

(c) If the liquid, still at half level, has a 5 cm thick layer of foam on top of it, what effect will this have on the signal amplitudes seen from part (b)? [20%]

(d) How can the top transducer alone be used to measure the foam thickness directly, and what signal levels would be expected for the same pulse drive as in part (b)? [20%]

(e) Liquid flow out of the tank is measured by a flow sensor comprising a PZT transducer at each end of a 20 mm diameter, 25 cm long tube, where the transducers face each other and are operated with continuous-wave, alternating excitation at 100 kHz. What is the change in signal phase shift between the pair of flow sensor transducers when the flow rate varies from 0 to 1 litre s^{-1} and hence, what is the average d.c. level change of the output from a 5 V CMOS logic XOR-gate phase detector? [15%]

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	-
PTFE	2200	1372	-
Sulphuric acid	1840	1258	0.01
Foam layer	120	200	85

3 An aerial drone is used to take thermal images of buildings to help identify areas of heat loss. The drone carries a downward facing pyrometer system and a LIDAR ranging system to measure height above the buildings.

(a) The pyrometer system detector comprises a 5 mm × 5 mm area array of 40 μm thick doped silicon thermocouples, divided into a 100 × 100 pixel array, supported on a 150 μm thick foam insulating layer above a base Si wafer substrate. The detector array is located 25 mm behind a ZnSe lens of diameter 10 mm. The various detector materials have the following physical properties:

Si conductivity: 3×10^{-2} Ω m, Si specific heat capacity: 0.70 J g^{-1} K^{-1}, Si density: 2330 kg m^{-3}, foam density: 3.0 kg m^{-3}, foam thermal conductivity: 0.020 W K^{-1} m^{-1}.

(i) Calculate the thermal rating of the entire thermal detector array. [10%]

(ii) Calculate the 10% - 90% response time of the detector array. [15%]

(iii) What is the imaging resolution on a building when the drone is at a height of 20 m above, and how slow must the drone fly for accurate thermal imaging? [10%]

(iv) Calculate the difference in thermocouple voltage signals when imaging building surface areas at 5 °C and 15 °C, assuming a surface emissivity of 0.90. [20%]

(b) The detector array substrate has a pair of Si bipolar transistor current mirrors defined in it, with an area ratio of 9:1 between the load transistors, to produce a signal proportional to the substrate temperature. Explain how this circuit operates and derive the relationship between the output voltage signal and substrate temperature. [20%]

(c) The LIDAR system comprises a pulsed 5 mW near-infrared laser of wavelength 850 nm with a narrow beam pointing downwards. The time-of-flight of the laser pulses are determined by detecting the back-scattered light with a 25 mm diameter collection lens focusing the light received onto a photodiode with a quantum efficiency of 75%.

(i) Calculate the pulse-echo delay time at a height of 50 m. [5%]

(ii) At 50 m, what is the magnitude of the detected photo-current if the surface may be considered to have Lambertian properties with a reflectivity of 40%? [10%]

(iii) How can the system be optimised to minimise the effects of ambient light? [10%]

The Seebeck coefficient for Si is given by: $P_S = 2.6\,(k/q)\,\ln(2\times10^{5}\,\rho)$.

State all assumptions and approximations made.

4 (a) Describe the process steps utilized for the fabrication of surface micro-machined gyro sensors on a planar substrate, explaining how the structures and clearances between components are defined, and how the sensor structures are driven and motion sensed. [20%]

(b) A polysilicon surface micro-machined gyro sensor has 100 capacitor pairs on each axis to provide sensing and/or excitation functions. The out-of-plane thickness of the structural layer is 8 µm, the nominal air-gap between the electrodes is 1 µm and the length of each electrode is approximately 500 µm. On the drive axis, half the electrodes are used for excitation and half for sensing. The proof mass has dimensions of 350 µm × 750 µm, suspended by tether springs on each corner, allowing movement in both x and y axes. The tether springs on each axis can be considered as straight beams, each 150 µm long with a thickness of 2 µm.

(i) Estimate the total capacitance per axis. [10%]

(ii) Calculate the total spring constant for the tether beams on each axis. [20%]

(iii) Estimate the mechanical resonant frequency of the sensor structure. [15%]

(iv) What magnitude of drive voltage is required to sustain an oscillation amplitude of 0.5 µm at resonance if the mechanical Q-factor is 85? [15%]

(v) What is the amplitude of the raw sensor signal in response to an angular rotation rate of 90º s^{-1} if the differential capacitance sensing electrodes are supplied with a potential difference of 2 V a.c.? [20%]

The density of polysilicon is 2330 kg m^{-3} and its Young's modulus is 150 GN m^{-2}.

State all assumptions and approximations made.

END OF PAPER

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