Version PAR/3

EGT3
ENGINEERING TRIPOS PART IIB

Friday 27 April 2018 2 to 3.40

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.

1 Rural houses are often heated by an oil-fired boiler, where the oil is stored in a large rectangular steel tank placed in the garden. The tank walls are 3 mm thick. A remote readout of the oil level in the tank is achieved by using an ultrasonic sensor, mounted underneath the base of the tank, operating in pulse-echo mode to determine the liquid level by time-of-flight. The ultrasonic transducer is made from PZT and has the following properties: electrical impedance = 500 Ω, diameter = 20 mm, electro-mechanical efficiency = 25 %, full beam angle = 10 º.

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

(a) What is the pulse-echo delay time when the oil level is 0.65 m ? [10%]

(b) If the transducer is driven with a pulse of amplitude of 12 V, what is the open-circuit voltage of the received transducer reflection signal when the oil level is at:

(i) 0.65 m and

(ii) 0.15 m ? [50%]

(c) Unfortunately, water can sometimes collect in the tank due to condensation, or rain water seeping through rusted holes in the top of the tank. If 50 mm of water has collected in the bottom of the tank, how would this affect the signal timing and amplitude in comparison to the water-free case, for a total liquid level of 0.65 m, and what affect does this have on the apparent oil level reading ? [20%]

(d) Explain how the water level and oil level can be measured independently from the pulse-echo signals and calculate the relative magnitude of the two liquid level signals under the conditions described in part (c). [20%]

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
Steel	7600	5960	23
Water	1000	1500	0.7
Heating Oil	810	1324	0.7
PZT	7500	4000	-

2 (a) A sports aircraft built from carbon fibre composites uses some of the structural fibre yarns, which have a nominal resistance of 1.2 kΩ, as strain gauges to monitor the in-flight dynamic loads on the wings. If the gauge factor of the carbon fibres is 1.5 and a full-bridge is implemented with strain gauging on the top and bottom of the wing, design an interface circuit to give an output signal voltage of 5 V at a strain of 0.2 % when the circuit is powered from a supply of +12 V d.c. [25%]

(b) An accelerometer based on MEMs technology is to be implemented in the aircraft as a G-meter with a range of ±100 m s^{-2} (i.e. approximately ±10 G). The accelerometer proof mass has dimensions of 600 μm × 200 μm with a thickness of 7 μm and is suspended by a 2 μm wide 'hair-pin' tether spring at each corner with a semi-length of 100 μm. Fifty sets of capacitive electrodes 100 μm long are situated on each side of the proof mass, with a nominal air gap of 1.5 μm between the electrodes.

(i) Describe in outline the physical and chemical processes used to fabricate a surface micro-machined accelerometer based on poly-silicon technology. [20%]

(ii) Calculate the total capacitance between the electrodes. [10%]

(iii) Calculate the spring constant for the proof mass suspension. [20%]

(iv) What is the fractional change in capacitance when the device is exposed to a full-scale acceleration of 100 m s^{-2} along the sensing axis in open-loop mode ? [10%]

(v) If 40 % of the capacitor electrodes are used for sensing and 60 % for force feedback in closed-loop mode, calculate the feedback voltage required to balance the full-scale acceleration. What are the advantages of closed-loop operation ? [15%]

State all assumptions and approximations made.

Silicon density = 2330 kg m^{-3}

Silicon Young's modulus = 110 GN m^{-2}

3 (a) In order to calibrate the response of a pyrometer, a surface temperature probe comprising an ntc semiconductor thermistor is attached to a test surface to provide a reference measurement. If the thermistor has a resistance of 1 kΩ at 20 ºC and a β' value of 3200 K, what resistance will it have when at a temperature of 60 ºC ? [10%]

(b) Recent fires in lithium battery packs for electric aircraft have prompted the inclusion of a smoke detector within such packs, to warn the pilot of a problem before it becomes catastrophic. Such a smoke detector comprises a 1 mW, 635 nm laser diode in proximity to a 1 mm^2 Si photodiode with a quantum efficiency of 60 %. The presence of smoke scatters the light sideways where it is detected by the photodiode; which would otherwise not be illuminated since the device axes are orthogonal.

(i) If the presence of smoke scatters 0.1 % of the laser light isotropically and the photodiode is situated an average distance of 50 mm from the laser beam axis, what is the magnitude of the resulting photo-current from the diode ? [20%]

(ii) In order to amplify this signal, a transimpedance amplifier with an input noise current density of 1.2 pA $Hz^{-0.5}$ is employed with a feedback impedance comprising a 10 MΩ resistance in parallel with a 10 nF capacitor. What is the amplitude and signal-to-noise ratio of the output voltage signal ? [25%]

(c) A pyrometer system to measure the surface temperature of a lithium battery pack during testing comprises a 5 cm diameter ZnSe lens placed 100 mm in front of a 5 mm diameter silicon-based thin film thermocouple. The thermocouple is fabricated on top of a large substrate, separated by a 250 μm thick insulating layer of silica foam, which has a thermal conductivity of 0.05 W m^{-1} K^{-1}, a specific heat capacity of 1200 J K^{-1} kg^{-1} and a density of 150 kg m^{-3}.

(i) What is the thermal rating of the thermocouple, expressed in ºC W^{-1} ? [10%]

(ii) If the thermocouple silicon is doped to a resistivity, $\rho = 2 \times 10^{-3}$ Ω m, what is the resulting signal produced when the battery surface temperature reaches 60 ºC, assuming a surface emissivity value of 0.95 ? [20%]

(iii) Estimate the bandwidth of the thermal detector. [15%]

State all assumptions and approximations made.

Note: the Seebeck coefficient for silicon, $Ps \approx 2.6\ k/q\ \ln(\rho\ /\ 5.6\times10^{-6})$

4 (a) An electric airliner is being developed to fly from London to Paris, propelled by 2 MW electric motors. The positive power cable to each motor carries a voltage of 500 V d.c. To monitor the motor current, a Hall effect sensor is mounted at a radial distance of 15 mm from the cable axis. The Hall sensor is made from a 250 μm square slice of silicon with a thickness of 15 μm, doped to a resistivity of 10^{-3} Ω m and supplied by 5 V d.c.

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

(ii) Derive the responsivity of the Hall sensor element and hence calculate the Hall voltage signal for the motor at full power. [20%]

(iii) How can another Hall sensor be added to improve the immunity to interference from other current carrying cables and increase the signal voltage ? [10%]

(b) The aircraft instrument panel supply current, which includes both a.c. and d.c. components, is to be monitored by a Hall sensor of the same type as that described in part (a). It is placed in the 0.5 mm air gap of a ferrite toroid with a relative permeability of 1500, a cross-sectional area of 30 mm^2 and average magnetic length of 50 mm. The supply cable is wound through the toroid 20 times to increase the sensitivity.

(i) What is the inductance of the current sensor seen on the supply cable ? [15%]

(ii) What is the Hall sensor output signal when the current is 0.5 A ? [15%]

(iii) Estimate the bandwidth of the Hall sensor and the thermal noise voltage likely to be seen in the output signal. [25%]

State all assumptions and approximations made.

Silicon carrier mobility = 0.16 $m^2 V^{-1} s^{-1}$

END OF PAPER

THIS PAGE IS BLANK