Version PAR/4

EGT3:IIB
ENGINEERING TRIPOS PART IIB

Monday 4 May 2015 2 to 3.30

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.

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

1 (a) Show how a number of bipolar transistors can be configured in a circuit to output a signal voltage directly proportional to absolute temperature. What transistor area ratio is required to give an output responsivity of 0.2 mV K^{-1} ? [25%]

(b) A pressure sensor located on a rocket utilises a sputtered thin-film NiCr strain gauge full-bridge, powered from a 5 V d.c. supply. If the rocket motor casing experiences a strain of 0.1 % when the nozzle pressure is 1 MPa and can change in temperature by 200 °C, what is the raw output voltage from the bridge and what is the largest possible error in the pressure reading if the temperature coefficient of resistance of the NiCr alloy is within +/- 5 ppm / °C ? [15%]

(c) The temperature of the batteries in a space satellite is monitored by an NTC (negative temperature coefficient) thermistor, supplied with a constant current excitation of 0.1 mA. The thermistor has a resistance of 10 kΩ at a temperature of 25 °C, a β' value of 4000, a contact area of 2 mm^2 and is attached to the batteries with an adhesive layer of thickness 50 μm.

(i) What is the output signal from the sensors when the battery temperature reaches 60 °C ? [15%]

(ii) If the adhesive layer has a thermal conductivity of 0.27 W m^{-1} K^{-1}, estimate the consequent error in the measured temperature. [15%]

(d) The fuel level inside a storage tank is monitored by an ultrasonic pulse-echo system using single PZT (lead zirconate titanate) transceiver transducers situated above and below the liquid surface, on the inside top and bottom of the tank. If the fuel tank has an internal height of 50 cm, what is the difference in the pulse-echo time delay from each transducer and what is the relative amplitude of the received voltage signals from the two transducers when the tank is half full ? Assume that each transducer is driven with electrical pulses of the same amplitude. [30%]

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	1
Fuel	0.73	1600	2
PZT	7500	4000	-

2 (a) Describe the process steps required for the fabrication of surface and bulk micro-machined MEMS devices and give an example of the types of structures which can be produced in each case. [35%]

(b) An acceleration sensor comprises a rectangular section silicon proof mass of dimensions 750 μm × 250 μm × 5 μm suspended on cantilever springs of width 2 μm attached to each corner, as illustrated by the plan view in Fig.1 below.

(i) Making suitable assumptions about the dimensions of the springs, estimate the resonant frequency of the sensor. [20%]

(ii) A self-test electrode structure is implemented in the design in the form of a fixed capacitor plate parallel to one end of the proof mass, with a 2 μm air gap between the two components. Estimate the amplitude of the drive voltage required on this electrode to cause a 1 μm amplitude oscillation of the proof mass at the resonant frequency, assuming a mechanical Q-factor of 150. [25%]

(c) An electronic interface for a MEMS device utilises an inverting operational amplifier circuit with a linear gain of 100, a bandwidth of 100 kHz and an input impedance of 10 kΩ. If the operational amplifier has a noise current density of 2 pA $Hz^{-1/2}$ and a noise voltage density of 3 nV $Hz^{-1/2}$, what is the minimum signal amplitude which can be detected assuming a signal to noise ratio of at least 10 dB is required ? [20%]

State all approximations and assumptions made.

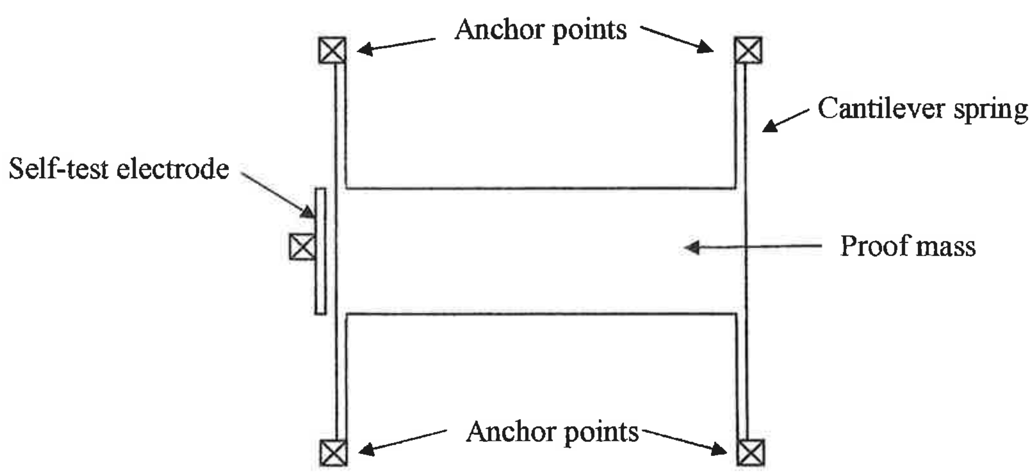

Fig. 1

3 A dual-purpose optical temperature sensing and ranging system is built into a space probe set in orbit around a distant comet. The optical system comprises a 10 cm diameter ZnSe lens, 12 cm behind which is placed a combined 640 nm wavelength laser source and wide-band optical detector of diameter 8 mm. The comet surface is found to have an emissivity of 0.85 and a Lambertian reflectivity of 0.50 at the wavelengths of interest.

(a) What is the optical power falling on the detector due to back-scattering of the laser ranging pulses of power 100 W when the probe is 22 km above the comet surface ? [25%]

(b) Estimate the change in infra-red power falling on the detector when the probe scans different parts of the comet surface, which varies in temperature from –50 °C to 10 °C, and what is the diameter of the area on the comet surface over which the temperature measurements are being made if the probe distance remains at 22 km ? [25%]

(c) (i) If the optical detector has a quantum efficiency of 0.5 at 640 nm and the signals are amplified with a transimpedance circuit using a feedback resistance of 100 kΩ, what is the amplitude of the output signal voltage ? [25%]

(ii) If the transimpedance circuit is based on an operational amplifier with an input noise current density of 0.1 pA $Hz^{-1/2}$ and a noise voltage density of 1 nV $Hz^{-1/2}$, what is the maximum bandwidth at which the ranging system might be expected to operate to achieve a signal-to-noise ratio of at least 5 ? [25%]

State all approximations and assumptions made.

4 A toroid of Permalloy magnetic alloy with an average diameter of 50 mm and a square section thickness (and height) of 5 mm has a 0.2 mm slot cut in it, to create a narrow air gap. The Permalloy has a relative permeability of 5800 with a temperature coefficient of 0.1 % K^{-1}. Two of these toroids are used in different sensors within a submarine: one is used to sense the current flowing in the electric drive motors, and the other is used to measure the strain in the hull of the vessel as it submerges.

(a) For the current sensor, a Hall effect element comprising a slice of silicon with dimensions of 1 mm × 1 mm × 0.05 mm and doped to a resistivity of 0.05 Ω m is placed in the air gap. If the Hall sensor is excited with a constant current of 10 mA, what is the signal voltage observed across the device when the motor supply cable, which passes through the centre of the toroid, carries 100 A ? [30%]

(b) As the motor supply cable heats up over a period of time, the temperature of the toroid rises by 25 °C. What error does this introduce into the current reading ? [20%]

(c) For the strain sensor, the toroid is attached to the walls of the hull such that an external pressure of 10 MPa causes that part of the hull to deflect inwards by 0.1 mm - so halving the air gap. If the toroid is wound with 200 turns to create an inductive sensor, what inductance is seen at the sea surface and by approximately how much does it change when the vessel dives to a depth of 500 m, assuming the toroid deflection is linear with pressure ? [25%]

(d) Estimate the –3 dB bandwidth of the current sensing system by considering both the response of the Hall element and the time-constant of the motor circuits, assuming the resistance and inductance of the motor windings to be 0.1 Ω and 20 μH, respectively. [25%]

State all assumptions and approximations made.

Note: the electron mobility in Si = 0.16 $m^2\ V^{-1}\ s^{-1}$

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4B13 2015 – Numerical answers

1 (a) r = 10.16
(b) 500 kPa
(c)(i) 0.244 V
(c)(ii) 0.0026 °C
(d) 1.16 ms, 3.25:1

2 (b)(i) 4.08 kHz
(b)(ii) 2.63 V
(c) 24 μV

3 (a) 2.28×10^{-10} W
(b) 2.70 – 1.04 = 1.66 mW, 1467 m dia. = 1.69 km^2
(c)(i) 6.65 μV
(c)(ii) < 1 .0 kHz

4 (a) 0.88 V
(b) 0.3%, 0.3 A
(c) 5.5 mH to 7mH
(d) 796 Hz (limited by L/R time constant)