EGT3
ENGINEERING TRIPOS PART IIB

Friday 26 April 2019 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 A Mars lander spacecraft is equipped with an ultrasonic wind-speed sensor system comprising a pair of transducers facing each other, separated by a distance of 0.4 m. The ultrasonic transducers are made from PZT/brass discs, fitted with aluminium cones to realise an acoustic impedance of 800 rayls, with the following physical properties: resonant frequency 150 kHz, electrical impedance = 1500 Ω, diameter = 15 mm, electro-mechanical efficiency = 20 %, full beam angle = 20 º.

(a) What is the zero wind-speed ultrasonic transit time between transducers when the system is tested on Earth and how does this change when on Mars ? [10%]

(b) If the transmitting transducer is driven with a waveform of amplitude 10 V, what is the open-circuit voltage of the receiving transducer signal when:

(i) on Earth or

(ii) on Mars ? [40%]

(c) If the wind velocity on Mars is 10 m s^{-1} at 45° to the transducer axes, what is the phase shift in the received ultrasonic signal compared to the zero wind-speed case? [15%]

(d) The temperature on the surface of Mars varies about an average value of – 63 °C by ± 80 °C. Given that the speed of sound in a gas varies with the square root of absolute temperature (in K), if left uncompensated, what difference would this temperature range make to the phase shift and amplitude of the transducer received signals ? [10%]

(e) After resting on the surface of Mars for some time, a 5 mm thick build-up of dust has occurred on the transducer surfaces. What effects will this have on the apparent wind-speed measured along the transducer axes, and how is the magnitude of the received signal changed ? [25%]

State all assumptions and approximations made.

Table 1 Physical properties of media

	Density ($kg\ m^{-3}$)	Speed of sound ($m\ s^{-1}$)	Attenuation ($dB\ m^{-1}$)
Air	1.2	340	2.5
Mars atmosphere	0.09	240	2.1
Mars dust layer	120	500	66

2 The cross-section of a MEMS device to scan a laser beam in a projection system is shown in Figure 1 (not to scale). It comprises a 1 mm square silicon tilting mirror supported all along one side by a flexure hinge which is 50 μm long and 2.5 μm thick. The silicon wafer is 250 μm thick. The mirror is deflected by the force from a capacitor plate situated under the mirror on a glass plate, across an air gap of 100 μm. The etch angle for the silicon is 35 ° to the vertical and the mirror deflects with up to 5 ° of tilt.

(a) Outline the MEMS fabrication processes used to construct the device shown in Figure 1, describing the key process steps. [20%]

(b) (i) Calculate the capacitance between the deflection electrodes at zero and maximum tilt angles. [20%]

(ii) Estimate the resonant frequency of the mirror structure and hence the deflection settling time, assuming a mechanical Q-factor of 40. [25%]

(c) To monitor the mirror deflection, two strain gauges are fabricated on the upper surface of the flexure hinge and a matching reference pair is situated on the wafer, away from the hinge. The strain gauges have a resistance of 10 kΩ, a gauge factor of 35 and are connected into a full bridge with a supply voltage of 5 V.

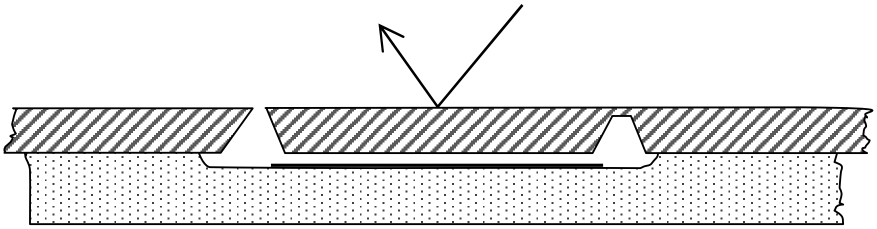
(i) Calculate the raw output signal from the strain gauge bridge when the mirror is tilted by 5 °, and the minimum tilt resolution which might be achieved. [25%]

(ii) Describe how the monitor signal could be used to optimise the projector performance and what benefits would be obtained. [10%]

State all assumptions and approximations made.

Silicon density = 2330 kg m^{-3}
Silicon Young's modulus = 110 GN m^{-2}

Figure 1 Cross section of MEMS laser beam scanner



3 A space probe landing on the far side of the moon carries a LIDAR system to map the lunar surface topography, and a pyrometer system to measure the surface temperature over the range −173 °C to 127 °C. Both systems share the same front collection optics: a ZnSe lens of diameter 50 mm focussing infra-red light onto two different photodiodes.

(a) The pyrometer detector element comprises a 4 mm diameter CdHgTe photodiode, with a peak response wavelength at 10 μm, situated 75 mm behind the ZnSe lens. If the quantum efficiency of this photodiode is 70 %, calculate the change in photocurrent as the surface temperature sweeps from its minimum to maximum value. You may neglect the effects of any spectral response variations and assume the emissivity of the lunar surface to have a value of 0.85. [25%]

(b) In order for the CdHgTe detector to work properly, it is cooled to −130 °C by a thermo-electric refrigerator using a thermistor to monitor the device temperature. A similar device is also used to measure ambient temperature. If the thermistor has a resistance of 100 Ω at 25 °C and a β' value of 4200 K:

(i) What will be its resistance at −130 °C ? [10%]

(ii) Calculate the non-linearity of its resistance over the range from 10 °C to 20 °C. [20%]

(c) The LIDAR system employs a 5 W, 850 nm laser collimated into a narrow beam. Calculate the photocurrent produced by the detector, which comprises a 1 mm^2 silicon photodiode with a responsivity of 0.8 A W^{-1} when the ranging distance is 25 m, assuming the lunar surface back-scatters light isotropically with a reflectivity of 35 %. [15%]

(d) If the lunar surface actually scatters light with a Lambertian distribution, show how the detected signal from part (c) will change if the LIDAR system views the surface area at an angle of 45 ° to the normal. [20%]

(e) Describe what measures should be taken in the LIDAR system design to ensure that it is unaffected by ambient sunlight. [10%]

State all assumptions and approximations made.

4 The magnetic field on the surface of Mars has a peak value of around 1.5 µT. A probe landing on the planet surface carries a fluxgate magnetometer to monitor the magnetic field in addition to a Hall effect sensor with flux concentrators, for comparative measurements. The required measurement bandwidth is around 10 Hz.

(a) Briefly describe the principles of operation of Hall effect and fluxgate magnetic sensing techniques. [25%]

(b) Design a fluxgate magnetometer system to produce an output signal with a responsivity of 1 V μT^{-1}. Assume a gating drive frequency of 25 kHz and a pair of magnetic cores, each of 1 mm diameter and 40 mm length with coils of 500 turns. [25%]

(c) The Hall sensor is made from a 300 µm square slice of silicon with a thickness of 10 µm, doped to a resistivity of $10^{-2}\ \Omega\ m$ and supplied by 5 V. It is placed between two high permeability cores, axially aligned end-to-end, acting as flux concentrators to increase the sensitivity. The core dimensions are the same as given in part (b).

(i) By what factor is the magnetic flux density increased through the use of the concentrating cores, assuming they are effectively in contact end-to-end ? [10%]

(ii) Derive the responsivity of the Hall sensor element and hence calculate the Hall voltage signal for the peak magnetic field detected. [15%]

(iii) Estimate the raw bandwidth of the Hall sensor and the thermal noise voltage present in the output signal. [25%]

State all assumptions and approximations made.

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

The demagnetising factor, D, of a core of length, ℓ, and diameter, d, is given by:

$$D = (d / \ell)^2\ [\ \ln(2\ \ell/d) - 1]$$

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<u>4B13 2019 Numerical answers</u>

1(a)	0.49 ms
1(b)(i)	0.339 V amplitude, open cct.
1(b)(ii)	0.039 V amp., o/c
1(c)	± 2650°
1(e)	1.3% wind speed under-measured, 27 µV amplitude
2(b)(i)	0.156 pF
2(b)(ii)	816 Hz, 49 ms
2(c)(i)	0.191 V, 8.6 x 10^{-5} °
3(a)	photo-current change = 9.68 mA
3(b)(i)	431 MΩ
3(b)(ii)	~ 1000 % (very non-linear)
3(c)	0.70 µA
3(d)	$I_L/I_{iso} = \sqrt{2}$
4(c)(i)	x 1570
4(c)(ii)	0.8 V/T, 1.89 mV
4(c)(iii)	58.6 kHz, 0.99 µV_{rms}