ENGINEERING TRIPOS PART IIB

Thursday 25 April 2013 9.30 to 11

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.*

There are no attachments.

STATIONERY REQUIREMENTS
Single-sided script paper
Graph paper

SPECIAL REQUIREMENTS
Engineering Data Book
CUED approved calculator allowed

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

1 (a) Briefly describe 3 different types of analogue-to-digital (ADC) converter and compare their relative advantages and disadvantages with reference to conversion speed and resolution. Draw a schematic block diagram for a sigma-delta converter and explain the concept of noise-shaping in this application. [25%]

(b) The temperature sensor in an engine management system monitoring the air intake temperature of a petrol engine uses a thermistor in a half-bridge with a 1 kΩ resistor to ground (0 V), where the mid-point connects to the ADC input of a micro-controller. The thermistor has a resistance of 500 Ω at 0 °C, with a β' value of 3100, and the circuit is supplied with 5 V d.c.

Calculate the ADC input voltages at 20 °C and 40 °C and estimate the non-linearity over this range compared to linear extrapolation from the 0 °C and 20 °C values to 40 °C. [25%]

(c) A paint thickness gauge uses a variable inductance sensor, comprising a U-shaped core of ferrite material, with a relative permeability, μ_r, of 1500, wound with 500 turns of copper wire. The cross-sectional area of the core is 0.1 cm^2 and its magnetic length is 25 mm. The non-magnetic paint spaces the open ends of the U-core away from the steel sheet beneath, creating an 'air-gap' in the magnetic path. Calculate the inductance change in the sensor for a change in paint thickness from 100 to 200 μm, assuming the steel sheet to have a large thickness and high relative permeability. [25%]

(d) An ultrasonic Doppler flow sensor is used to measure the flow rate of a refrigerant liquid Freon within a pipe of 6 mm bore diameter. The transducers operate at 5 MHz and are arranged with their beam at 45 ° to the pipe axis. Calculate the Doppler frequency observed for a flow rate of 20 $cm^3\ s^{-1}$ and draw a schematic block diagram of system electronics required to produce a logic level square wave at the Doppler frequency. The speed of sound in liquid Freon is 524 ms^{-1}. [25%]

State all assumptions and approximations made.

2 (a) Explain how miniature cantilever beam structures can be fabricated by surface and bulk micromachining techniques. Briefly describe the processing steps utilised in each technique to create the beam, its anchor point and clearance gap beneath. [30%]

(b) A sensor for monitoring air quality comprises a silicon cantilever $500\ \mu m$ long, $200\ \mu m$ wide and $5\ \mu m$ thick, coated with a thin (100 nm) polymer layer with a density of $1200\ kg\ m^{-3}$. Estimate the resonant frequency of the cantilever beam. [30%]

(c) When smelly organic molecules are present in the air, they are absorbed into the polymer layer on the cantilever in part (b) – increasing the polymer's mass by $10\ \%$. Estimate the shift in resonant frequency of the cantilever after its exposure to organic vapour. [15%]

(d) A capacitor electrode spaced $5\ \mu m$ beneath the cantilever beam over its entire area has a voltage applied to attract the beam, enabling it to be excited into resonance. Calculate the voltage required to deflect the end of the static beam by 100 nm . [25%]

State all assumptions and approximations made.

3 A survey aircraft flies at a height of 1000 m equipped with a pyrometer system to measure the ground surface temperature over large areas. The aircraft altitude above the ground is monitored at the same time with an optical pulse-echo ranging system using an infra-red laser pointing at the ground and a photo-detector in the aircraft.

The pyrometer system comprises an imaging array of 1 mm × 1 mm semiconductor thermistor elements with β' = 3500 and a resistance of 1 kΩ at 20 °C , arranged 20 cm behind a ZnSe lens of 10 cm diameter. The thermal rating of each thermistor element is 250 °C/W.

(a) If the ground temperature varies between 0 – 20 °C and has an average emissivity of 0.95 , what is the change in power falling on each thermistor element ? [25%]

(b) What is the difference in resistance between elements imaging ground areas with temperatures of 0 °C and 20 °C , and what area of land does each element image ? [20%]

(c) The optical ranging detection system comprises a photodiode in the centre of the array, at the focal point of the lens, with a quantum efficiency of 75% . What is the photo-current signal magnitude from a 850 nm wavelength laser pulse power of 100 W, assuming the ground surface is optically scattering with a reflectivity of 40 % and the air is totally clear ? Also, what is the pulse-echo transit time at this height ? [35%]

(d) Very often, the atmosphere contains water vapour and dust particles which absorb and / or scatter light such that a light beam is attenuated over a distance, expressed in dB km^{-1} . If the minimum detectable photo-current is 10 pA, what is the maximum optical attenuation which can be tolerated if the ranging system is to operate up to an aircraft altitude of 5000 m ? [20%]

State all assumptions and approximations made.

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

4 A non-destructive testing (NDT) system for carbon-fibre / epoxy composite aircraft components comprises a pair of co-located, identical ultrasonic transducers operating in pulse-echo mode to detect air voids and metal components within the composite skin. The PZT ultrasonic transducers operate at 8 MHz and have a diameter of 2 cm , a narrow beam angle and an electro-mechanical efficiency of 15 % .

(a) If the carbon-fibre composite wall is 5 mm thick, what is the pulse-echo delay time and the power transmission coefficient between the transducer and composite ? [20%]

(b) What amplitude of signal will be seen at the receiving transducer across a matched load of 5 kΩ when the transmitting device is driven with a 120 V pulse ? [35%]

(c) In order to increase the signal coupling efficiency, a matching layer is to be added to the front of the transducers. A candidate material has been identified which has a speed of sound of 2500 ms^{-1} . What layer thickness of this material is required and what should its optimum density be ? [15%]

(d) It is desired to make a low-powered, portable version of the system where the drive amplitude is reduced to 1.2 V and the received signal amplified to the same level as previously using an operational amplifier with the following noise parameters: $i_n = 2$ pA / $\sqrt{Hz}$ and $e_n = 8$ nV / $\sqrt{Hz}$. Estimate the signal-to-noise ratio for the pulse received from a 20 mm thickness of carbon-fibre composite using this system. [30%]

State all assumptions and approximations made.

	Density ($kg\ m^{-3}$)	Speed of sound ($m\ s^{-1}$)	Attenuation ($dB\ m^{-1}$)
Air	1	340	1
Carbon fibre / epoxy composite	1750	2850	32
PZT	7500	4000	-

Table 1: Physical properties of materials

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5 A non-contact inspection system for cracks in railway tracks comprises an array of powerful permanent magnets ahead of a linear array of magnetic sensors across the width of each rail. If there is a crack in the rail, the pre-magnetised steel produces fringing fields in the air gap across the crack and above the rail surface. The magnetic flux density is typically around 10 mT at the crack edges and decreases with the square of the ratio of the distance above the rail to crack width. The survey train runs along the tracks at a speed of $10\ ms^{-1}$ and is looking for cracks over 0.5 mm wide.

(a) Briefly describe the principle of operation of 3 different magnetic sensing techniques which may be suitable for this application. [30%]

(b) It is decided to evaluate silicon Hall effect sensors for this application, where the sensor elements are $200\ \mu m \times 200\ \mu m$ in surface area and $10\ \mu m$ deep and are excited with a voltage of amplitude 5 V. What is the amplitude of the raw signal created when a sensor moves over a 1 mm wide crack at a height of 2 mm above the rail surface ? [30%]

(c) Derive expressions for the rise-time and thermal noise voltage of the Hall sensor and determine the minimum crack size which may be detected at a height of 1 mm above the rail. [40%]

State all assumptions and approximations made.

The silicon has an *electron mobility* of $0.14\ m^2\ V^{-1}\ s^{-1}$ and a *resistivity* of $0.045\ \Omega\ m$.

END OF PAPER