UNIVERSITY OF CAMBRIDGE

ENGINEERING TRIPOS PART IIB

Monday 26 April 2004 2.30 to 4

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.

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

(TURN OVER

1 (a) A nominal 10 mA current from a new sensor under test is passed through a nominal 100 Ω 4-terminal resistor. The voltage so developed is measured on a digital voltmeter (D.V.M.) with an input resistance of 1 MΩ and 8 readings were:

1.0091 V 1.0072 V 1.0058 V 1.0083 V 1.0075 V

1.0072 V 1.0086 V 1.0063 V .

What is the mean sensor output current and what is the standard uncertainty in the measurement? [20 %]

(b) In order to calculate the system corrections and uncertainties, the main sources of these are known as:

- the D.V.M. when last calibrated 2 years ago was found to indicate 0.05 % higher than was correct and, from previous calibrations, this correction was found to be rising by 0.01 % per year with an uncertainty of 0.02 % per year since calibration.
- The 100 Ω resistor, last calibrated 3 years ago, was found to be 0.02 % higher in value than was correct. From previous calibrations, it's value was rising by 0.01 % per year with an uncertainty of 0.02 % per year since calibration.
- The temperature coefficient of the D.V.M. and of the resistor are both known to be negligible but the uncertainty of stating this is 0.02 %/ °C for the D.V.M. and 0.01 %/ °C for the resistor. The sensor measurement was done in conditions ± 5 °C different from that of the calibration lab.

Determine what now is the correct indicated current from the sensor. [25 %]

(cont.

(c) Complete an uncertainty budget for the measurement in a tabular form with the following column headings:

Source of Uncertainty; Value in %; Probability; Divisor; Standard Uncertainty in %.

The uncertainties of value previously given for the D.V.M. and the resistor are both expanded with a $\times 2$ multiplier to represent a 95 % confidence level. All other uncertainties are not expanded.

Determine the combined uncertainty in % that you would quote for your result based on a Standard Uncertainty expanded with a $\times 2$ multiplier to give a level of confidence of approximately 95 % for the result.

What gives the biggest contribution to the measurement uncertainty and suggest briefly how to reduce it ? [30 %]

(d) Explain carefully the features of a 4-terminal resistor. Why is this type essential for a 100 Ω or lower value standard resistor ? [25 %]

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2 Faulty power transformers that are overheating can often be detected remotely by the use of thermal imaging equipment. A thermal imaging camera comprises a ZnSe lens of diameter 5 cm in front of an infra-red (IR) detector consisting of a 256×256 array of micro-thermocouples. The micro-thermocouples have an individual thermal rating of 1.3×10^4 °C W^{-1} and a Seebeck coefficient of 67 $\mu V\ K^{-1}$.

(a) Calculate the total thermal power radiated by a transformer of surface area 0.65 m^2 when at a temperature of 85 °C, assuming an emissivity value of 0.73. [15 %]

(b) What is the IR power collected by the thermal imaging camera lens when the camera is at a distance of 10 m from the transformer and what electrical signal level does this produce in the detector array if the collected IR radiation is focussed onto 12 % of the array elements ? [50 %]

(c) Estimate the signal-to-noise ratio of the transformer thermal image if the micro-thermocouples and associated signal switching components have a total resistance of 50 Ω, the pre-amplifiers have a noise voltage of 1.2 nV $Hz^{-1/2}$ and the signal bandwidth is 200 Hz. What surface temperature would give a unity signal-to-noise ratio ? [35 %]

State all assumptions and approximations made.

Note: the Stefan-Boltzman constant $= 5.6 \times 10^{-8}\ W\ m^{-2}\ K^{-4}$

3 (a) Describe briefly what is meant by *bulk Si micromachining* and *surface micromachining* with particular reference to micro-electro-mechanical systems (MEMS) and sensor applications. Illustrate your answer with cross-section diagrams showing the main fabrication steps. Comment on the prospects for integrated MEMS with readout electronics on the same silicon substrate. [30 %]

(b) With reference to the schematic plan view of the surface micromachined acceleration sensor with capacitative readout shown in Figure 1, describe the main features of the device, identify the sensitive axis and outline what is meant by the terms:

open loop operation and *electrostatic force-feedback operation* . [30 %]

(c) Taking the silicon proof mass thickness to be $3\ \mu m$, the minimum electrode separation to be $0.8\ \mu m$, the other dimensions as in Figure 1, and making sensible estimates of any other unknown quantities, make an order-of-magnitude calculation of the accelerometer device capacitance. Calculate the magnitude of the applied voltage in the force feedback mode that would be required to maintain the proof mass in a fixed position when the sensor is subjected to an acceleration of $60\ ms^{-2}$. [40 %]

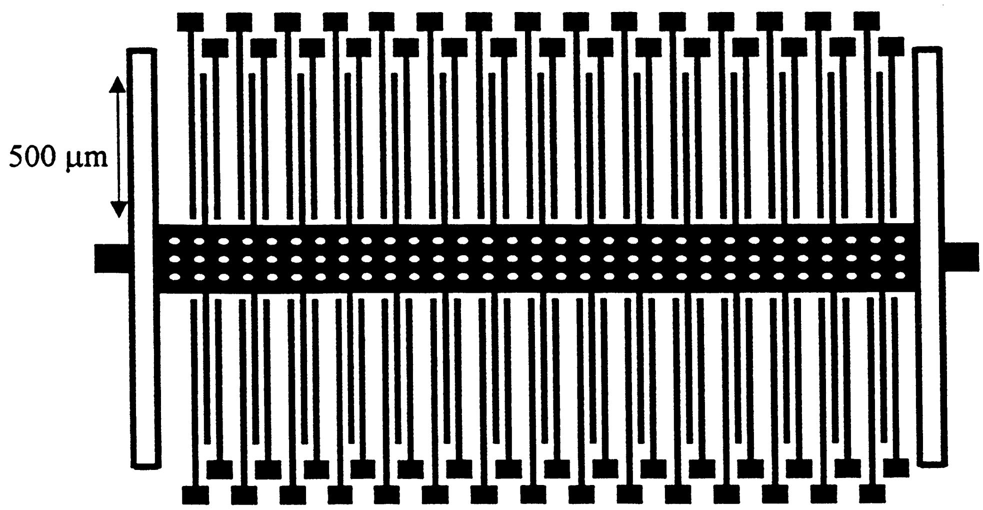

Figure 1

(TURN OVER

4 (a) Sketch a block diagram of the main functional components of a fluxgate magnetometer system, which produces an analogue output voltage proportional to the magnetic field detected. [20 %]

(b) Derive an expression for the sensitivity of a single-core fluxgate sensor, in terms of the amplitude V_2 of the second harmonic of the drive frequency f, produced when the sensor is exposed to a magnetic field of flux density B. Include terms describing the geometry of the coil and core and state all approximations and assumptions made.

Also, estimate the self-inductance of the sensor. [55 %]

(c) Calculate the amplitude of the second harmonic signal produced when a fluxgate sensor, comprising a 400 turn pick-up coil with a high permeability core of diameter 0.2 mm and length 10 mm, is driven at optimum level with a 25 kHz gating signal, whilst being subject to the Earth's horizontal magnetic field component of 25 μT. What value capacitor should be connected across the pick-up coil to maximise the amplitude ratio of the second harmonic signal to the gating drive signal ? [25 %]

Note: The demagnetising factor D of a high permeability core of length l and diameter d may be approximated by: $D = (d/l)^2\,[\ln(2l/d) - 1]$.

5 An engineer is learning to fly his light aircraft but is having trouble judging height during the final approach for landing. The usual air-pressure based altimeters are not sufficiently accurate for this, so he plans to fit an ultrasonic ranging system, with combined pulse-echo and Doppler modes, to indicate both the height above ground and the rate of descent.

A pair of ultrasonic transducers with an electrical impedance of $200\ \Omega$, diameter of 7 cm and designed for operation at 40 kHz are fitted to the aircraft; pointing directly downwards. They have an acoustic impedance of $2400\ \mathrm{Kg\ m^{-2}\ s^{-1}}$ and a conversion efficiency of 10 %.

(a) What is the Doppler frequency detected and the pulse-echo transit time when the aeroplane is at a height of 50 m and decending at a rate of $1\ \mathrm{m\ s^{-1}}$? [20 %]

(b) If the transmitter transducer is driven with a $240\ V_{p\text{-}p}$ waveform, what is the acoustic power density at ground level when the aircraft is 50 m above, if the transducer beam angle is $\pm 5°$? [30 %]

(c) Calculate the open-circuit amplitude of the electrical signal produced by the receiver transducer when the aircraft height is 50 m, assuming that the ground surface scatters back 25 % of the incident ultrasonic energy equally in all directions. [40 %]

(d) Comment on the technical feasibility of such a system. [10 %]

Note: 40 kHz ultrasonic attenuation coefficient in air = $0.15\ \mathrm{dB\ m^{-1}}$

Speed of sound in air = $340\ \mathrm{m\ s^{-1}}$

Density of air = $1.29\ \mathrm{Kg\ m^{-3}}$

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