ENGINEERING TRIPOS PART IIB

Monday 5 May 2008 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.

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 The casing of a high performance electric motor used in an electrically powered aircraft needs to be monitored to prevent over-heating. This is achieved by bonding a surface mount thermistor onto the casing with epoxy adhesive. In order to provide a robust signal for transmission to the control unit microprocessor, the thermistor is connected into an RC oscillator circuit which produces an output frequency, $f = 1/RC$ Hz.

(a) If the semiconductor thermistor to be used has the following properties: $R = 1000\ \Omega$ at 20 °C and $\beta' = 3000$, and the oscillator capacitor value is 10 nF, calculate the change in oscillator frequency over a temperature range of 50 °C to 100 °C . [25%]

(b) If the microprocessor interprets the oscillator frequency to be linearly related to the temperature, what is the true motor temperature when the microprocessor reads 80 °C if the linear calibration factor was determined at 50 °C ? [25%]

(c) The thermistor has a mass of 0.1 g and is bonded to the motor with a 0.25 mm thickness of epoxy adhesive over a surface area of 0.5 cm^2. The thermal properties of the various components are given below:-

Specific heat capacity of epoxy and thermistor = 1.2×10^3 J kg^{-1} K^{-1}
Thermal conductivity of epoxy resin = 0.35 W m^{-1} K^{-1}

Calculate the thermal rise-time of the thermistor in response to a sudden change in motor temperature. [25%]

(d) In order to measure the thrust from the electric propulsion system, the motor and its propeller are mounted at the top of a test stand comprising a solid rectangular steel rod, the base of which is set into the ground. The rod has a thickness of 5 mm and a height above ground of 1 m. A full bridge of 4 metal strain gauges is mounted onto the post at a height of 10 cm above the ground, and the motor is mounted with its axis level with the top of the post. The strain gauge bridge is powered by a 5 V supply, and its output voltage displayed on a digital voltmeter.

What should be the width of the rod for the output signal to have a scale factor of 1 mV per kg force of thrust, assuming the rod to be stressed in its direction of minimum stiffness ? [25%]

State all assumptions and approximations made.

2 (a) Explain the concepts of *surface micromachining* and *bulk micromachining* in the context of the fabrication of Micro-Electro-Mechanical Systems (MEMS). When is monolithic integration of MEMS with CMOS electronics desirable ? [30%]

(b) Compare and contrast the advantages of capacitive sensing versus piezoresistive sensing in the context of a MEMS pressure sensor application. [20%]

(c) Explain the differences between operating a capacitive MEMS accelerometer in *open-loop* mode versus *force-feedback* mode. [15%]

(d) A single-axis polysilicon surface micromachined accelerometer employs differential capacitive pick-off with 100 capacitive electrode pairs providing in-plane acceleration sensing. The out-of-plane thickness of the structural layer is 6 μm , the nominal gap between the electrodes is 1 μm and the length of each electrode is approximately 500 μm . The proof mass weighs 1 μg and the spring constant for motion along the sensitive axis is 10 N m^{-1} . Estimate the following parameters for the accelerometer:

(i) The total sense capacitance of the accelerometer.

(ii) The fractional change in capacitance for an input acceleration of 10 m s^{-2}. [35%]

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3 (a) A nominal 1 mA current from a new sensor under test is passed through a nominal 1000 Ω 4-terminal resistor. The voltage so developed is measured on a digital voltmeter (DVM) with an input resistance of 1 MΩ and 8 readings, in volts, were:-

1.0091 1.0072 1.0058 1.0083 1.0075 1.0072 1.0086 1.0063

What is the mean sensor output current and 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 DVM when last calibrated 3 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 1000 Ω resistor, last calibrated 4 years ago, was found to be 0.02 % higher in value than was correct. From previous calibrations, its value was found to be rising by 0.01 % per year with an uncertainty of 0.02 % per year since calibration.
- The temperature coefficient of the DVM and of the resistor are both known to be negligible but the uncertainty of stating this is 0.02 %/°C for the DVM and 0.01 %/°C for the resistor. The sensor measurement was done in conditions ± 5°C different from that of the calibration laboratory.

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

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

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

The DVM and the resistor uncertainties of value are both expanded with a ×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 ×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%]

4 A large steel vat of chemicals in a paint factory has a pair of identical ultrasonic sensors mounted directly above it, to measure the level of liquid in the tank. The system works on the pulse-echo principle, monitoring the flight time through the air of ultrasonic pulses reflected back from the liquid surface. The ultrasonic transducers have a diameter of 2 cm, a full beam angle of 20°, an acoustic impedance 10 times that of air and an efficiency of 15 %. The physical properties of various materials are given in table 1.

(a) If the base of the vat is 2 m below the transducers, what is the ultrasonic pulse transit time observed when the vat is empty, and by how much is the pulse attenuated over the propagation distance ? [10%]

(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 12 V pulse and the vat contains a 1 m level of liquid ? [40%]

(c) During the paint mixing process, a 5 cm thick layer of foam builds up on the surface of the liquid. Also, the airspace above the liquid becomes saturated with organic solvent vapour, so increasing its density by 10% and decreasing the speed of sound by a similar amount. What effects will these changes have on the ultrasonic measurement system and how could they be compensated ? [25%]

(d) How would the signals differ if the same transducers were instead operating in the liquid, mounted at the bottom, on the inside of the vat facing upwards ? [25%]

	Density ($kg\ m^{-3}$)	Speed of sound ($m\ s^{-1}$)	Attenuation ($dB\ m^{-1}$)
Air	1	340	1
Paint	850	1350	12
Foam	15	300	55
Steel	7600	6500	3

Table 1: Physical properties of materials

State all assumptions and approximations made.

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5 In order to screen for a large number of different biological and pharmaceutical molecules, miniature analysis systems are being developed which comprise micro-fluidic channels formed on top of a silicon substrate. Chemicals are pumped through the channels and miniature magnetic beads, coated with various reagents, are introduced into the flow. In order to count and identify the beads, miniature Hall Effect magnetic sensors are defined in the silicon.

(a) Briefly describe the principles of operation of a Hall Effect magnetic sensor. [15%]

(b) If the sensor elements are 10 μm x 10 μm in surface area and 1 μm deep, what signal is created when a magnetic bead slides directly over its surface, producing an average vertical flux density of 10 mT over the active area, when the Hall sensor is excited by a current of 0.1 mA ? [30%]

(c) Derive an expression for the rise-time of the Hall sensor and therefore surmise the bandwidth of the device and the maximum bead velocity that could be detected. [40%]

(d) Calculate the impedance of the sensor element and the thermal noise voltage which may be expected. Hence estimate the maximum bead sensing distance which may be achieved, assuming the magnetic flux density from a bead to obey an inverse-cube relationship with distance from the bead centre. The nominal bead diameter is 10 μm. [15%]

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

State all assumptions and approximations made.

END OF PAPER