ENGINEERING TRIPOS PART IIB

Monday 2 May 2011 9 to 10.30

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.*

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

PAR05

1 An ultrasonic remote control system for a ceiling mounted projector in a lecture theatre uses PVDF transducers at an operating frequency of 100 kHz. The hand-held transmitter unit drives its transducer with a 20 V_{pp} amplitude. The transmitter transducer has an impedance of 350 Ω and a conversion efficiency of 15% , whilst the receiver transducer has an electrical impedance of 2 kΩ with a conversion efficiency of 10% . Both transducers have a matching cone on the front, which reduces the effective acoustic impedance of the PVDF by a factor of 1000 . The physical properties of various materials are given in table 1.

(a) What is the magnitude of the ultrasonic power transmitted into the air ? [25%]

(b) If the transmitted beam angle is 20 ° and the system operates over a range of 5 metres, what is the amplitude of the electrical signal across the receiving transducer when driving a high impedance circuit, if the transducer has a diameter of 5 wavelengths ? [25%]

(c) An engineer from the projector company decides to build an automatic cat-flap opener for his ageing cat, based on a spare pair of transducers. He intends to use a Doppler detector circuit to detect the motion of his cat, which has a frontal area of 10 cm × 20 cm and a reflectivity of 50% , coming towards the flap. Given the same 20 V drive level as above, what raw signal amplitude and beat frequency would be expected if the cat moves at 1 m s^{-1} , when at a range of 1 metre ? [30%]

(d) Draw a schematic diagram for a circuit to actuate a 12 V relay from the receiver transducer signal in part (c) when the moving cat is detected at close range. [20%]

State all assumptions and approximations made.

	Density (kg m^{-3})	Speed of sound (m s^{-1})	Attenuation (dB m^{-1})
Air	1.2	340	6
PVDF	1768	2250	-

Table 1: Physical properties

2 (a) Explain the concepts of *surface micromachining* and *bulk micromachining* in the context of the fabrication of Micro-Electro-Mechanical Systems (MEMS). Briefly outline the process steps used and the types of structures which can be produced by the different techniques. [30%]

(b) A dual-axis polysilicon surface micro-machined sensor has 200 capacitive electrode pairs on each axis to provide sensing and/or force feedback functions. The out-of-plane thickness of the structural layer is 6 μm, the nominal gap between the electrodes is 2 μm and the length of each electrode is approximately 500 μm. The proof mass has dimensions of 500 μm × 500 μm and the spring constant for each axis is 2 N m^{-1}. Estimate the following parameters for the accelerometer:

(i) The total capacitance per axis.

(ii) The fractional change in capacitance for an acceleration of 50 m s^{-2} along one axis, when operating in open-loop mode.

(iii) The voltage produced in force-feedback mode, if half the electrodes are used for sensing and half for force feedback. [35%]

(c) The same structure as in part (b) is to be used as a gyroscopic sensor, to measure rate of rotation. If the Q-factor of the structure in resonance is 100, and half the electrodes on each axis are used for driving and half for open-loop capacitive sensing:

(i) What magnitude and frequency of drive voltage is required to sustain an oscillation amplitude of 1 μm at resonance ?

(ii) What is the amplitude of the raw sensor signal in response to a rotation rate of 180° s^{-1} , if the differential capacitor sensing electrodes are supplied with a potential difference of 5V ? [35%]

State all assumptions and approximations made.

3 A hybrid electric car employs a 20 kW electric motor in parallel with a small petrol engine. The electric drive operates at 180 V d.c. and a Hall sensor, placed in the air gap of a 30 mm diameter toroid with 0.5 cm^2 cross-section surrounding the motor power cable, is used to monitor the current drawn or generated by the motor.

(a) If the Hall sensor is placed in a 1 mm air gap and the toroid is made of magnetic material with a relative permeability, $\mu_r = 500$, what is the magnetic flux density detected by the Hall sensor when the electric motor is running at full power ? [20%]

(b) The Hall sensor is fabricated with a 500 μm × 500 μm section of 6 μm depth in silicon. What is the Hall sensor output voltage at full power, when the device is powered with a 5 V supply ? [20%]

(c) Calculate the response bandwidth of the current sensor. [25%]

(d) Calculate the impedance of the sensor and hence estimate the thermal noise level for the sensor and express this as an equivalent measured current noise. [20%]

(e) If the Hall sensor output drifts by 0.1 mV $°C^{-1}$ and the thermal rating of the device is 10 °C W^{-1}, what will be the offset drift in the measured current due to self-heating of the sensor ? [15%]

State all assumptions and approximations made.

The silicon has a *carrier mobility* of 0.14 $m^2 V^{-1} s^{-1}$ and a *resistivity* of 0.06 Ω m.

4 (a) Derive the relationship between the optical intensity, seen at normal incidence, for a laser beam scattered from a Lambertian surface and that scattered from an isotropically back-reflecting surface. [20%]

(b) A 1 mW, 635 nm continuous wave laser beam with twin-frequency amplitude modulation at 100 MHz and 110 MHz is used in an optical 'tape measure'. If the collection lens has a diameter of 20 mm, what is the optical signal power received when the device is operating at maximum range, assuming a Lambertian target surface with a reflectivity of 70 % ? [30%]

(c) If the quantum efficiency of the photodiode in the system of part (b) is 80 % , a 1 MΩ feedback resistor is used in the transimpedance amplifier circuit and the input noise current of the operational amplifier is 0.10 pA $\sqrt{\text{Hz}^{-1}}$, what is the signal-to-noise ratio of the system at maximum range if two readings per second are required ? [25%]

(d) If the optical tape measure was to be used in a dusty environment where the laser beam is attenuated by 3 dB m^{-1}, what would be the maximum range of the system assuming a signal-to-noise ratio of at least 12 dB is required for correct operation ? [25%]

State all assumptions and approximations made.

5 An engineer puts some sensors and instrumentation onto a bicycle in order to measure the amount of power expended in pedalling it along. To achieve this, a pair of metal foil strain gauges are bonded onto the pedal crank arms 20 mm from the main sprocket rotation axis and 230 mm from the pedals. The pedal crank arms are fabricated from a hollow square, mild steel tube, with external dimension of 20 mm, and a 2 mm wall thickness.

Each 200 Ω strain gauge has a mass of 0.1 g and is bonded to the crank with about 0.20 mm thickness of epoxy adhesive over a surface area of 0.25 cm^2. The thermal properties of the various components are given below:

Specific heat capacity of epoxy and foil = 1.2×10^3 J kg^{-1} K^{-1}
Thermal conductivity of epoxy resin = 0.25 W m^{-1} K^{-1}

(a) What is the raw output signal from the strain gauges when a load of 50 kgf is placed on the pedal, if the strain gauge pair is connected as a half-bridge and driven by a 5 V supply ? [30%]

(b) It transpires that an offset voltage is seen in the raw signal once the strain gauges have warmed up due to self-heating. The offset is traced to there being a 0.05 mm difference in the epoxy thickness bonding each strain gauge to the crank arm. Assuming that the resistance of each foil strain gauge is proportional to absolute temperature (K), what is the magnitude of this raw offset voltage, and what pedal force is it equivalent to? [40%]

(c) Calculate the thermal rise-time of the strain gauges, as they heat up due to self- heating, when their electrical supply is applied. [30%]

State all assumptions and approximations made.

END OF PAPER

4B13 ELECTRONIC SENSORS & INSTRUMENTATION

NUMERICAL ANSWERS 2011

1(a) 7.22 mW

1(b) 0.426 mV rms into open cct.

1(c) 5.74 pW, 0.214 mV rms into open cct.

2(b)(i) 2.66 pF

2(b)(ii) 0.44 %

2(b)(iii) 0.725 V

2(c)(i) 3.81 kHz, 0.245 V

2(c)(ii) 0.033 V

3(a) 0.118 T

3(b) 82.6 mV

3(c) 18.4 kHz

3(d) 2.35 mA rms

3(e) 3.4 mA

4(a) Lamb. twice as bright

4(b) 0.311 nW

4(c) 354:1 or 51 dB

4(d) 5.01 m

5(a) 3.42 mV

5(b) 1.07 mV = 15.6 kgf

5(c) 8.5 s rise-time