The University of Melbourne

Semester Two 2004

Department: SCHOOL OF PHYSICS
Subject Number: 640-381
Subject Title: PRINCIPLES AND APPLICATIONS OF SENSORS

Exam Duration: 3 Hours

Reading Time: 15 Minutes

This paper has 6 pages

Authorised Materials:

Calculators are permitted in accordance with the rules of the Faculty of Science. They should not have been programmed nor should they store additional information.

Instructions to Invigilators:

This exam paper may be retained by the students.

Instructions to Students:

Attempt **ALL** questions. Total marks=100.

Paper to be held by Baillieu Library

Useful Expressions

$\lambda_b = 2nD$

$$B_c(T) = B_c(0K)\left[1 - \left(\frac{T}{T_c}\right)^2\right]$$

$T \approx exp(-2\alpha s)$

$$\alpha = \frac{\sqrt{2m(U - E)}}{\hbar}$$

$$\mu = \frac{m_1 m_2}{m_1 + m_2}$$

$$B = \frac{\mu_o I}{2\pi r}$$

$$\omega^2 = \frac{k}{\mu}$$

$2d \sin\theta = n\lambda$

$$p = \frac{h}{\lambda}$$

$$E = \frac{1}{2}kx^2$$

$Q = d_{11}F$

$$C = \frac{\varepsilon_0 A}{d}$$

$Q = CV$

$$R = \frac{\rho l}{A}$$

$E = hf - \varphi$

$$\Delta f = \frac{2fv\cos\theta}{c_s}$$

$$\Delta x \Delta p_x \geq \hbar/2$$

Useful values

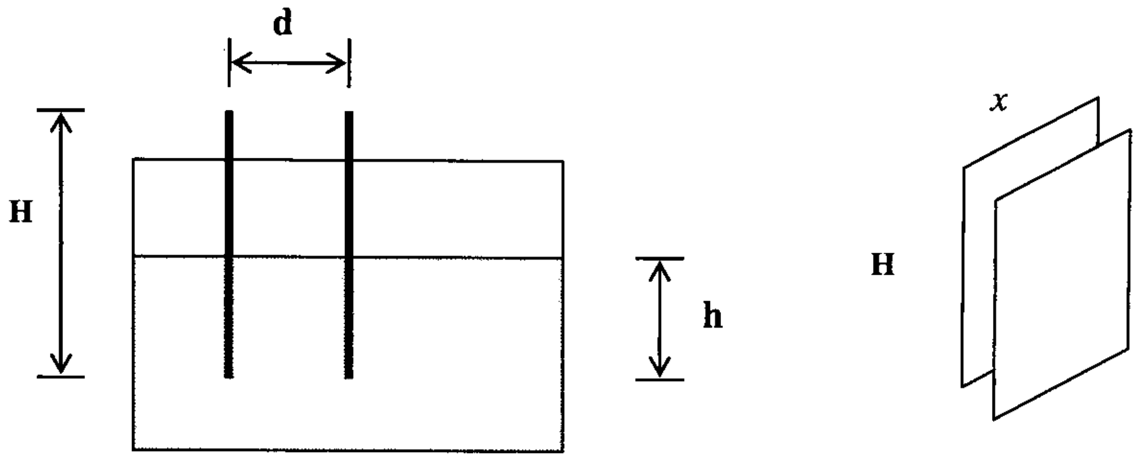
$\mu_o = 4\pi \times 10^{-7}$ N/A^2
Boltzmann's constant $k_B = 1.381\times10^{-23}$ J/K
Planck's constant, $h = 6.63\times10^{-34}$ Js
The mass of the carbon atom is 12 atomic mass units
The mass of the oxygen atom is 16 atomic mass units
1 atomic mass unit = 1.661×10^{-27} kg
Electronic charge = 1.602×10^{-19} C
$\varepsilon_0 = 8.854\times10^{-12}$ F/m
Acceleration due to gravity = 9.8 m/s
Density of Hg=13.595 g/cm^3
1 atm=101325 Pa

Question 1 (17 marks)

(a) Define the following terms as they apply to sensors, using a diagram in each case:

i. Hysteresis.
ii. Dead band
iii. Saturation

(3+3+3=9 marks)



(b) A fluid level sensor may be constructed by partially immersing two parallel conducting plates in water (we assume that the water does not conduct electricity). A schematic diagram is shown above. The capacitance of such a sensor is given by

$$C(h) = \frac{x\varepsilon_0[H - h(1-\kappa)]}{d}$$

Where x is the length of the bottom edge of the plates, d is the separation between the plates, κ is the dielectric constant of the liquid in which the plates are immersed, and h is the level to which the plates are immersed in the liquid (i.e. h=0 is completely out of the water, and h=H is completely immersed). In this case, H=20 cm, x=5cm, d=2mm and κ_{water} =78.5.

(i) What is the difference in the capacitance between when the plates are fully immersed and when they are fully out of the water?
(ii) Is the transfer function linear?
(iii) What is the sensitivity of this sensor?
(iv) Describe two ways that we could improve the sensitivity of this sensor.

(3+1+2+2=8 marks)

Question 2 (13 Marks)

(a)

(i) What is the difference between piezoelectric and pyroelectric sensors? Include a simple sketch.

(ii) Give an example of a sensing application for each type of sensor.

(4+2=6 marks)

(b) A piezoelectric force sensor is constructed from a 1 mm thick piece of $BaTiO_3$ with an electrode area of 1 cm^2. The piezoelectric constant d_{11} for $BaTiO_3$ is 78 pC/N. The dielectric constant κ for $BaTiO_3$ is 1700.

(i) If a force of 0.5 N is applied to the sensor, what charge will develop on the electrodes?

(ii) What voltage will be generated on the electrodes as a result of this charge?

(iii) What is the sensitivity of this sensor?

(2+3+2=7 marks)

Question 3 (13 marks)

(a) A steam furnace operates in a pressure range of 10-15 atm. An open-tube manometer filled with mercury is used to measure the pressure inside the furnace.

(i) If the pressure in the furnace is 12.34 atm, what is the height difference in the manometer at maximum pressure? Include a diagram in your answer.

(ii) Is this a good sensor for this application? Justify your answer.

(4+2=6 marks)

(b) An ultrasonic Doppler flow meter is commonly used to measure the flow speed of blood in arteries.

(i) Outline the operation of an ultrasonic Doppler flowmeter. Include a diagram.

(ii) If the speed of sound in blood is 1500 m/s and the frequency of outgoing and incoming pulses is 1.00 MHz and 1.05 MHz respectively, what is the speed of the blood? (Assume that the transmitters are aligned at 15° to the artery of interest).

(4+3=7 marks)

Question 4 (6 marks)

(a) A pellistor is a sensor that is used to detect the presence of flammable gases. It consists of a coil of platinum wire embedded in a ceramic bead. The oxidation of flammable gases increases the temperature and hence the resistivity of the wire according to $\rho = \rho_0[1+\alpha(T - T_0)]$, where T_0=293 K, ρ_0=1.69 μΩ.cm and α=3.9x10^{-3} K^{-1}.

(i) Describe two ways to increase the sensitivity of a pellistor.

(ii) A Pellistor is made using a wire of diameter 0.1 mm and length 3 cm. What is the increase in resistance for the pellistor arising from an increase in temperature from 400 K to 450 K?

(2+4=6 marks)

Question 5 (11 marks)

(a) The work function of sodium is 2.3 eV. Photoelectrons are emitted from sodium when the surface is irradiated with light of frequency 1.5×10^{15} Hz. What voltage is required to suppress the emission of these electrons?

(3 marks)

(b) The thermal energy spectrum emitted by a body is given by

$$E = \varepsilon \frac{8\pi h f^3}{c^3} \frac{1}{e^{hf/kT} - 1}.$$

(i) What is ε in the above expression?

(ii) Show that the ratio of the energies emitted at two known frequencies is a function only of temperature

(iii) Using your answers to parts (i) and (ii), describe the operation of a two-colour pyrometer.

(2+3+3=8 marks)

Question 6 (11 marks)

(a) The rotational energy levels of the carbon monoxide (CO) molecule are given by the expression

$$E_l = \frac{\hbar^2}{2I} l(l+1)$$

Where l is the rotational quantum number and I is the moment of inertia of the system.

The l=0 to l=1 rotational transition of the CO molecule occurs at a frequency of 1.15×10^{11} Hz.

(i) Sketch an energy level diagram for the rotational energy levels of CO..

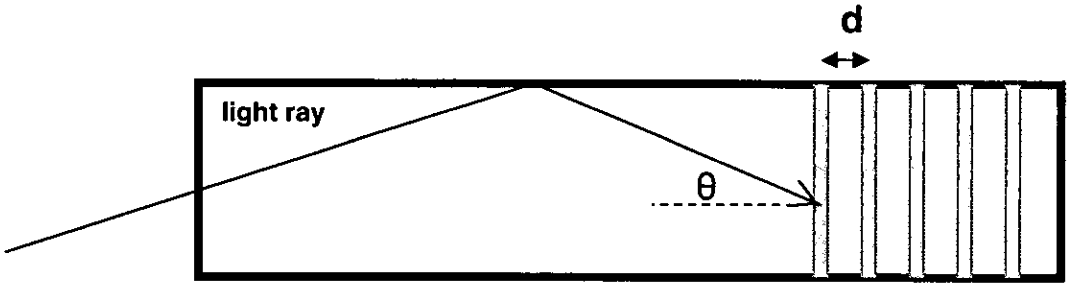
(ii) What is the moment of inertia of the CO molecule?

(iii) What is the reduced mass, μ, of the CO molecule?

(iv) Using this information, and recalling the fact that the rotational inertia I is related to the separation R of the two masses by $I=\mu R^2$, calculate the bond length of the molecule.

(3+3+2+3=11 marks)

Question 7 (12 marks)



Optical fibre

(a) Optical fibres can be modified with periodic variations in their refractive index. Such variations are often called Bragg gratings. A schematic diagram is shown above.

(i) Show that the condition for reflection at the Bragg grating is

$$n\lambda = 2d\cos\theta$$

where n is the order of reflection, λ is the wavelength of light in the fibre, d is the distance between variations and θ is the angle of incidence of the light on the grating.

(ii) How can such a sensor be used to count the number of cars passing over a section of road?

(4+3=7 marks)

(b) An air rifle is used to shoot 1g particles at 100 m/s through a hole of diameter 2 mm.

(i) How far from the rifle must an observer be to see the beam spread by 1 cm because of the uncertainty principle?

(ii) Compare this answer with the diameter of the known universe (1×10^{26} m).

(4+1=5 marks)

Question 8 (17 marks)

(a) One of the highest precision sensors of structure is the Scanning Tunnelling Microscope, or STM. It is capable of atomic level resolution

(i) Describe how quantum mechanical tunnelling allows the STM to achieve such high resolution. Include a diagram in your answer.

(ii) How does this differ from the operating principle of the Atomic Force Microscope (AFM)?

(iii) Describe the two main modes of operation of the STM.

(4+2+4=10 marks)

(b) When cooled to low temperatures, many metals become superconducting. For example, tantalum (Ta) displays type I superconductivity below a critical temperature of 4.47 K.

(i) The critical magnetic field above which type I superconductivity breaks down at absolute zero is 0.0829 Tesla. What is the critical magnetic field at 4.2 K?

(ii) The magnetic field B at a distance r from a wire carrying current I is given by $B = \frac{\mu_0 I}{2\pi r}$. If a Ta wire of radius 3 mm is carrying a current of 15 A, describe what will happen as the wire is heated from 4 K to 5 K.

(2+5=7 marks)

END OF EXAM