PART IIB 2011 DR P A ROBERTSON

4B13 CRIB - 2011

ELECTRONIC SENSORS AND INSTRUMENTATION

1 (a) $P_{trans} = \frac{V_{rms}^2}{R} \cdot \eta_{trans} \cdot \frac{4 Z_{air} Z_{trans}}{(Z_{air}+Z_{trans})^2}$

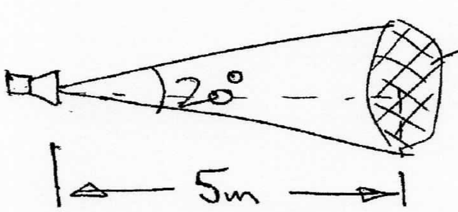
$Z_{air} = 1.2 \times 340 = 408 \text{ kg m}^{-2}\text{s}^{-1}$

$Z_{PVDF} = \frac{1768 \times 2250}{1000} = 3978 \text{ kg m}^{-2}\text{s}^{-1}$

$V_{rms} = \frac{20 V_{pp}}{2\sqrt{2}} = 7.07 \, V_{rms}$, $\eta_{trans} = 0.15$, $R = 350\Omega$

$\therefore P_{trans} = 0.143 \times 0.15 \times 0.337 = \underline{7.22 \text{ mW}}$ [25%]

(b) $\lambda = \frac{340}{100 \times 10^3} = 3.4 \text{mm}$ $\therefore$ transducer $\phi = \overset{5\times}{17 \text{mm}}$



$A = \pi (5 \tan 10°)^2 = \mathbf{2.44 m^2}$

Over 5m, attenuation = 6×5 = 30 dB

$P_{received} = \frac{\frac{\pi}{4}(17\times10^{-3})^2 \cdot 7.22 \text{mW} \cdot 0.337 \cdot 0.1}{2.44 \cdot 10^3} = \mathbf{226} \text{ pW}$

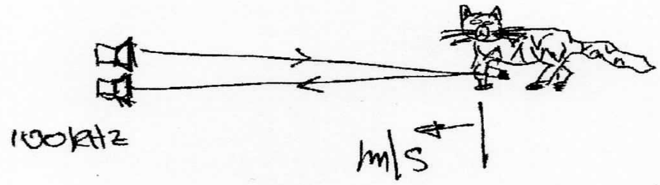
$= \frac{V_r^2}{2000}$

$\therefore V_r = 213 \, \mu V$ rms into matched load

or $\underline{0.426 \text{ mV}_{rms}}$ into open cct.

($\equiv$ 1.2 mV pp into cct) [25%]

(c)



- assume normal incidence
- area of cat 0.02 m²
- reflectivity of cat say 0.5 into hemisphere

Doppler beats/sec @ 1m/s $= \frac{2}{3.4\times10^{-3}} = \underline{588 \text{ Hz}}$

Received signal $= P_{trans} \times \text{coupling} \times \eta_{cat} \times \eta_{rec} \times \left(\frac{A_{cat}}{\pi(\tan 10°)^2}\right) \times \frac{A_{trns}}{2\pi \, \text{range}^2} \times \text{atten.}$

$= 7.22\times10^{-3} \cdot 0.5 \cdot 0.1 \cdot 0.337 \cdot \frac{0.02}{0.0977} \cdot \frac{\frac{\pi}{4}(17\times10^{-3})^2}{2\pi} \cdot 10^{-12/10}$

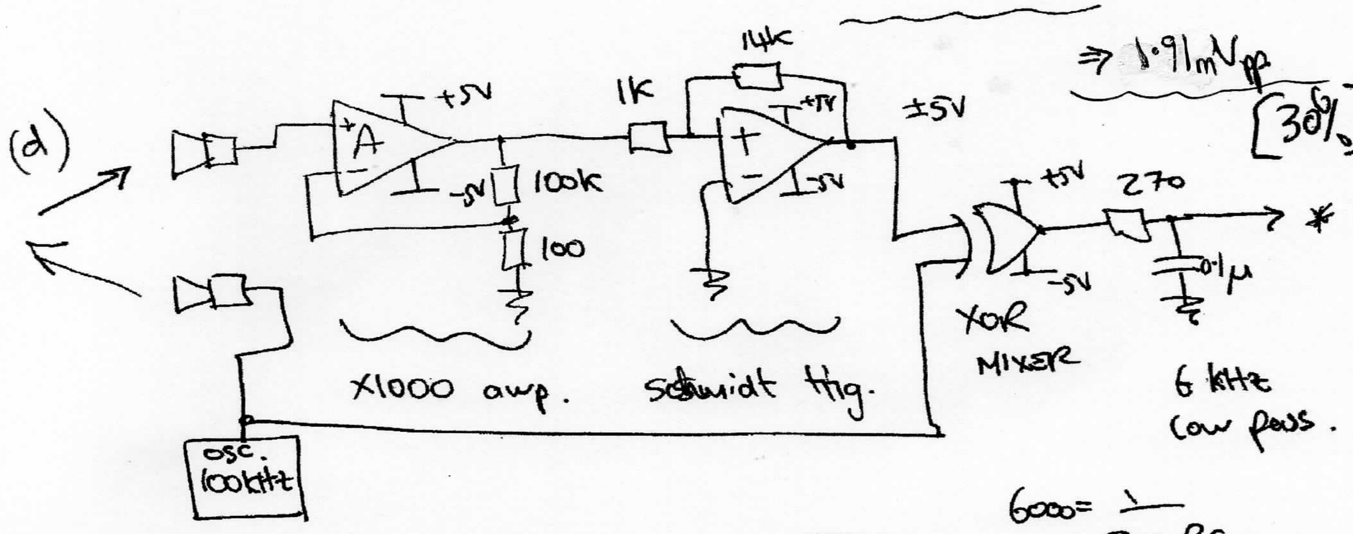
$= 56.8 \text{ pW}$

1(c) contd. $56.8 \times 10^{-12} = \frac{V_r^2}{2000}$ $\therefore V_r = 0.337$ mV rms into 2kΩ load
or 0.674 mV rms into open cct.

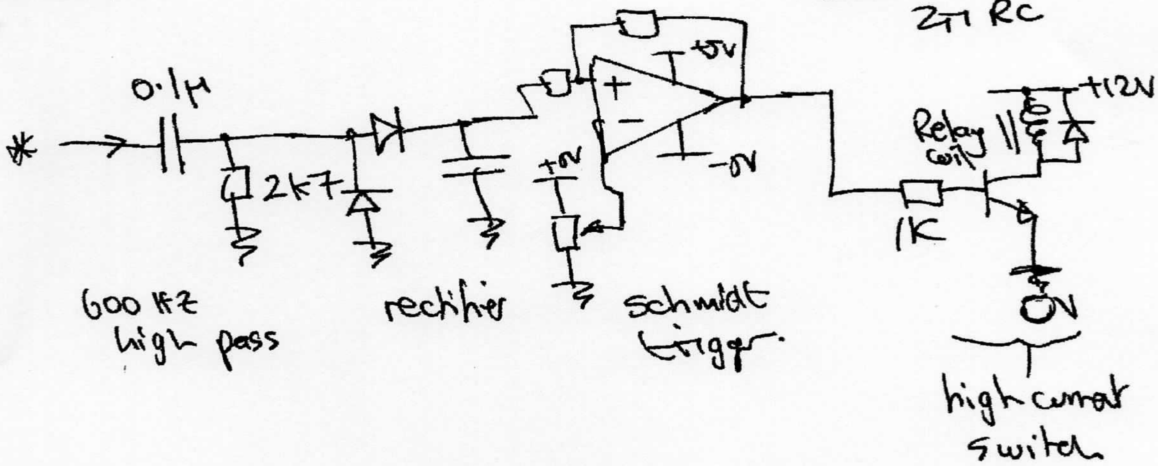
⇒ 1.91 mV pp

[30%]

(d)



$6000 = \frac{1}{2\pi RC}$



- Circuit functions
  - amplification
  - clean up sine wave to square wave
  - freq. mixing + discrimination
  - bandpass filter for min/max velocity
  - demodulation of ac signal
  - level detection
  - power stage to drive relay.

[20%]

Examiner's comment:

A very popular and straightforward question, which was well answered by most candidates. Some used the wrong beam angle, but the method was correct. The last part on an interface circuit was rather variable in quality, but there were some very good attempts.

2(a) • Description of surface & bulk structures
- examples: pressure sensor - bulk
accelerometer - surface

- Etching RIE, KOH
dry, wet

- Deposition of poly-Si, SiO_x, Si_3N_4, metals

- Sacrificial layers + etch masks + etch stops
- Layer bonding - anodic
- wafer
- adhesive
- outline of photolithography
spin-on resist, expose, develop, etch, remove

with simple diagrams illustrating these. [30%]

(b)(i) $C = \frac{A\epsilon_0}{d} = \frac{200 \times 6\times10^{-6} \times 500\times10^{-6} \times 8.854\times10^{-12}}{2\times10^{-6}}$

$= 2.66\,pF$

(ii) $m = (500\times10^{-6})^2 . 6\times10^{-6} . 2.33\times10^3$ and $F = ma = xS$

$a = 50\,ms^{-2}$, $S = 2\,Nm^{-1}$ with $m = 3.495\times10^{-9}\,Kg$

$\therefore F = 17.5\times10^{-8}\,N \Rightarrow x = 87.4\times10^{-9}\,m$

$\therefore$ fractional change in capacitance =

$\frac{87.4\times10^{-9}}{2\times10^{-6}} = 44\times10^{-3} = 0.44\%$

(iii) Feedback capacitance $= \frac{2.66}{2} = 1.33\,pF$

$E = \frac{1}{2}CV^2 \therefore \delta E = F\,dx = \frac{1}{2}V^2\,\delta C$

2(b)(iii) cont'd.

$$\therefore F = \frac{1}{2} V^2 \frac{dC}{dx} \quad , \quad C = \frac{A\epsilon_0}{x}$$

$$\therefore \frac{dC}{dx} = \frac{-A\epsilon_0}{x^2} = \frac{-C}{x}$$

$$\therefore F = \frac{1}{2} \frac{CV^2}{x} = \frac{1}{2} \frac{C^2 V^2}{A\epsilon_0}$$

$$\Rightarrow \quad 17.5 \times 10^{-8} = \frac{1}{2} \cdot \frac{1.33 \times 10^{-12}}{2 \times 10^{-6}} V^2 \qquad \therefore V = 0.725\,V$$

[35%]

(c)(i) $2\pi f = \sqrt{\frac{S}{m}} \quad \Rightarrow \quad f = 3.81\ kHz$

For drive amplitude, with Q of 100, drive force = 1/100 of static case for 1μm deflection:

@ 2 N/m ⇒ 2×10^{-8} N, & from (b)(iii) above

$$\Rightarrow \quad V = 0.725 \times \sqrt{\frac{2 \times 10^{-8}}{17.5 \times 10^{-8}}} = 0.245\,V$$

(ii) Coriolis $\Omega = 180°/s = 3.14$ rad/s

$a_L = 2 v_{\parallel} \Omega$ from data book (mechanics)

If resonant at $f = 3.81$ kHz with 1μm amplitude

$$x = 10^{-6} \sin 2\pi f t$$

$$\dot{x} = v_{\parallel} = \underbrace{2\pi f\, 10^{-6}}_{\to\ 0.024\ m/s} \cos 2\pi f t$$

$$\therefore a_L = 2 \cdot 0.024 \cdot 3.14 = 0.15\ ms^{-2}$$

$$\therefore F_L = 0.15 \times 3.495 \times 10^{-9} = 0.524 \times 10^{-9}\,N \qquad (m \times a)$$

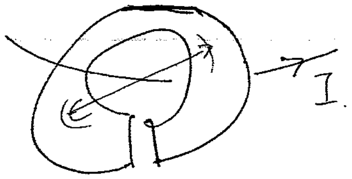
$$\therefore y = \frac{0.524 \times 10^{-9}}{2} \cdot 100 = 26.2\ nm \qquad (m \times Q/s)$$

$$\therefore V_{out} = \frac{26.2\ nm}{2\ \mu m} \times \frac{5V}{2} = 0.033\,V$$

[35%]

Examiner's comment:

A fairly popular question, although details of materials and processing was often missing in the fabrication descriptions. Most candidates made a good attempt at the accelerometer device calculations although the additional complexity of the gyro stalled many.

3(a). 

$\frac{20kW}{180V} = 111\ A$

$\oint H.dL = I \quad \therefore \quad H_m \times l_m + H_g \times l_g = I$

$l_m = (30\times10^{-3} \times \pi) - 10^{-3} = 93.2\times10^{-3}\ m$

$l_g = 10^{-3}\ m$

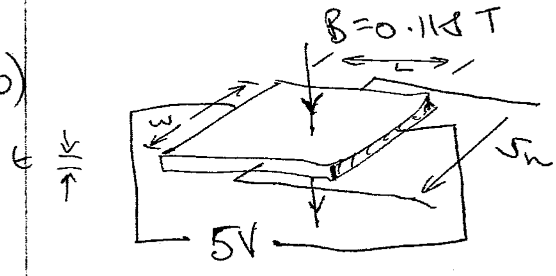
$B = \mu H$ with $B_g = \mu_0 H_g$ and $B_m = \mu_0\mu_r H_m$

also $B_g = B_m \quad \therefore \quad H_m = H_g/\mu_r$

$\therefore I = H_g \times \frac{l_m}{\mu_r} + H_g l_g \quad \therefore \quad 111 = H_g\left(\frac{93.2\times10^{-3}}{500} + 10^{-3}\right)$

$\therefore H_g = 93.6\times10^{3}\ A/m$

$\therefore B_g = \mu_0 H_g = 0.118\ T$ [20%]

(b) 

$I = nqv_d$

F (carrier) $= v_d q B = qE = q\frac{V_h}{w}$

drift velocity. $v_d = \frac{V}{L}\cdot\mu = \frac{5}{0.5\times10^{-3}}\cdot 0.14 = 1400\ m/s$

$\therefore V_h = w v_d B = 500\times10^{-6}\times1400\times0.118 = 82.6\ mV$ [20%]

$S = 0.70\ V/T$

$\equiv 7.44\times10$

V/A

(c) $R = \frac{\rho l}{A} = \frac{0.06\ .\ \cancel{500\times10^{-6}}}{\cancel{500\times10^{-6}}\ .\ 6\times10^{-6}} = 10\ k\Omega$

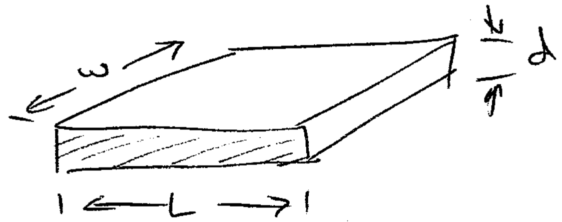
$V_n = \sqrt{4kTRB}$ with $B = 18.4\ kHz$

$\therefore V_n = 1.75\ \mu V\ rms \equiv 2.5\ \mu T\ rms \equiv 0.00235\ A\ rms$

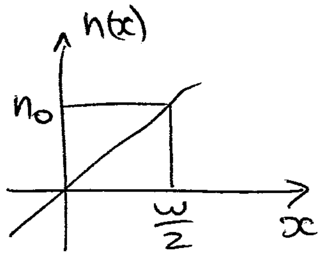
(2.4 mA rms.)

[20%]

3(c)



From derivation in notes, assume linear excess carrier conc.



$$n(x) = \frac{2n_o}{w}x$$

$$\therefore \frac{dn}{dx} = \frac{2n_o}{w}$$

Carrier flux across centre line $f = -D\frac{dn}{dx}$ with $D = \frac{\mu kT}{q}$

$\therefore$ Total excess carriers each side $N = Ld\int_0^{w/2} \frac{2n_o x}{w}\,dx$

where $\frac{dN}{dt} = f \times \text{area} = -DLd\frac{dn}{dx}$

$\Rightarrow \frac{dN}{dt} = -\frac{8D}{w^2}N$ soln. of form $N = N_o e^{-t/\tau}$

where $\tau = \frac{w^2}{8D}$ time constant

$\therefore f_{-3dB} = \frac{1}{2\pi\tau} = \frac{4D}{\pi w^2} = \frac{4\mu kT}{q\pi w^2}$ $= 18.4\text{ kHz}$

for dimns of Si

[25%]

3(e) $P = \frac{V^2}{R} = \frac{25}{10000}$ W

$\therefore \Delta T = 10 \times P = 0.25°C$

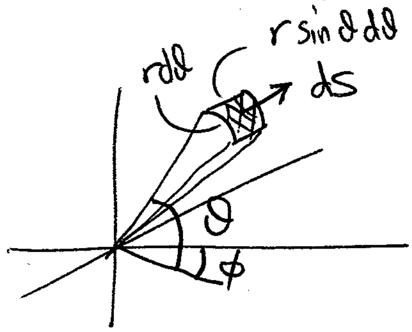
$\therefore \Delta v = 2.5\mu V \equiv 3.4\text{ mA}$

[15%]

Examiner's comment:

A very popular and well attempted question, which was quite straightforward in nature. The magnetic flux density, sensor response bandwidth and impedance were quite well handled, but the last parts on noise and thermal drift proved more challenging for most.

4(a)



for Lambertian case
$I = I_o \cos\theta$

$$P_{total} = \int_0^{2\pi}\int_0^{\pi/2} I_o \cos\theta \, dS$$

$$P = \int_0^{2\pi}\int_0^{\pi/2} I_o \cos\theta \, r^2 \sin\theta \, d\theta \, d\phi$$

$$= 2\pi \int_0^{\pi/2} I_o \cos\theta \, r^2 \sin\theta \, d\theta$$

$$= 2\pi \int_0^{\pi/2} I_o r^2 \frac{\sin 2\theta}{2} \, d\theta$$

$$P = \left[-\pi I_o r^2 \frac{\cos 2\theta}{2}\right]_0^{\pi/2} = I_o \pi r^2$$

∴ vs. isotropic case into ½ sphere where $I_o = P/2\pi r^2$

the Lambertian case is 2x brighter @ max. [20%]

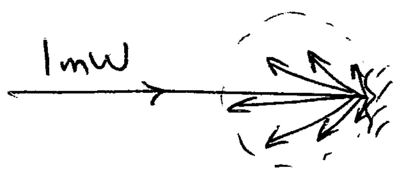
4(b) with $c = 3\times10^8$ m/s

$f = 100$MHz $\quad \lambda = 3$m

$f = 110$MHz $\quad \lambda = 2.727$m

∴ phase difference repeats every 10/11 λ's = 30m path

∴ Max. range $= \frac{30}{2} = 15$ m for non-ambiguity



For 70% Lambertian reflectivity
0.7mW reflects with $I = I_o \cos\theta$

∴ at 15m, the intensity @ normal incidence is $\frac{0.7\times10^{-3}}{\pi . 15^2}$ for a Lambertian surface $\quad I = \frac{P_o}{\pi R^2}$

(or ½ for isotropic scatter)

∴ Power received $= \frac{\pi (20\times10^{-3})^2}{4} \cdot \frac{0.7\times10^{-3}}{\pi . 15^2} = \underline{0.311 \text{ nW}}$

$\frac{\pi d^2}{4}$ for lens.

[30%]

4(c) cont. B/w for 2 readings/sec = 5 Hz say

V_n 1M. resistor $= \sqrt{4kTRB} = 0.28\ \mu V$ rms

V_n op-amp $= 0.1\times10^{-12}\times10^{6}\times\sqrt{5} = 0.22\ \mu V$ rms.
$(i_n \times R)$

$\left(\Sigma v_n^2\right)^{1/2} = 0.36\,\mu V$

$\therefore\ S/N = \dfrac{127\ \mu V}{0.36\ \mu V} = \underline{\underline{354}} \approx 51\ dB$

[25%]

4(d) $12 dB = \times 4\ \therefore$ min signal $= 1.12\,\mu V.$

$$\frac{0.311\ nW}{\left(\frac{0.127\ mV}{1.12\ \mu V}\right)} = 2.74\ pW \qquad \text{or } \frac{1}{113} \text{ of signal @ 15m}$$

Beam is attenuated by 6 dB per metre of range & inverse square law ∴

$$\text{Signal received} = \frac{0.7\times10^{-3}}{\pi R^2}\cdot\frac{\pi(20\times10^{-3})^2}{4}\cdot 10^{-\frac{6R}{10}} = 2.74\times10^{-12}$$

$$\therefore\ 10^{-0.6R} = 3.91\times10^{-5} R^2$$

eg: Solve by iteration

eng:	R = 5	0.001 =	0.000978	quite close
	5.1	8.70×10^{-4}	1.017×10^{-3}	worse
	4.95	1.07×10^{-4}	0.958×10^{-4}	worse
	5.01	9.86×10^{-4}	9.81×10^{-4} ~~≈~~	close enough!

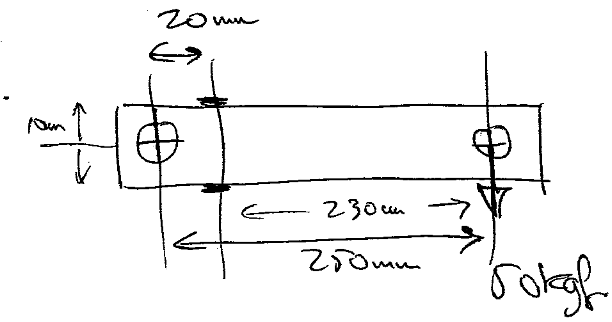
$\underline{R = 5.01\,m}$

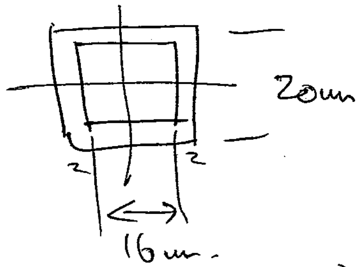
[25%]

Examiner's comment:

A very unpopular question only attempted by a 1 undergrad. and 1 postgrad., and both of these were partial attempts. The first part on Lambertian back-scatter was from the notes and answered well, however, deriving the maximum range and signal strength proved too difficult (even both are in the notes). This topic was new to the course this year.

5(a).



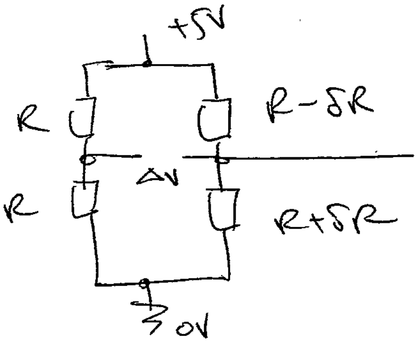


$I = \frac{1}{12}\left(b_e d_e^3 - b_i d_i^3\right)$

$= 7.87 \times 10^{-9}\ m^4$.

$\frac{\sigma}{y} = \frac{M}{I}$ $\qquad \sigma = \epsilon E$

assume gauge factor = 2.



$\Delta V = \frac{5}{2}\left(\frac{\delta R}{R}\right)$

$y = 10 \times 10^{-3}$ m

$M = 50 \times 9.81 \times 0.23 = 113$ Nm

$\frac{\sigma}{10 \times 10^{-3}} = \frac{113}{7.87 \times 10^{-9}}$ $\qquad \therefore \sigma = 143.6$ MN/m²

$\epsilon = \frac{\sigma}{E} = \frac{143.6 \text{ MN/m}^2}{210 \text{ GN/m}^2}$

$\therefore \epsilon = 6.84 \times 10^{-4}$

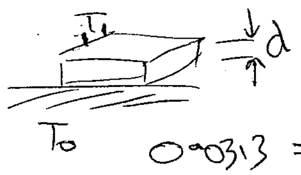
$\therefore \frac{\delta R}{R} = 2 \times \epsilon = 1.37 \times 10^{-3}$

$\therefore \Delta V = 3.42$ mV

[30%]

(b) Heating per gauge: $\frac{V^2}{R} = \frac{2.5^2}{200} = 0.0313$ W.

Heat flow $F =$



$\frac{\Delta T\, kA}{d}$

$0.0313 = \frac{\Delta T \; 0.25 \; 0.25 \times 10^{-4}}{0.200 \pm 0.025 \times 10^{-3}}$

0.175 − 0.225

ΔT's

$= 0.25$ °C $\left\{ \begin{array}{l} \Delta T_1 = 0.8764 \\ \Delta T_2 = 1.1268 \end{array} \right.$

5(b) cont

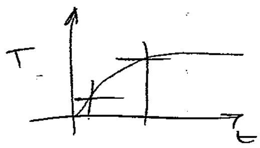
$$\frac{0.25\,K}{293\,K} = 8.53\times10^{-4} = 2\frac{\delta R}{R}.$$

$$\therefore V_o = \frac{5}{2}\left(\frac{\delta R}{R}\right) = 1.07\ mV$$

$$\Rightarrow 15.6\ kgf \quad (153\,N)$$

[40%]

(c) Rise time:



Heat flow: $F = mc_p\dot{T} = -T\frac{kA}{d}$

soln. $T = T_o e^{-t/\tau}$

$$\dot{T} = -\frac{T_o e^{-t/\tau}}{\tau} = \frac{-T}{\tau} \quad \therefore \quad \tau = \frac{mc_p d}{kA}$$

time constant.

$$\tau = \frac{0.1\times10^{-3} \cdot 1.2\times10^{3} \cdot 0.2\times10^{-3}}{0.25 \cdot 0.25\times10^{-4}} = 3.84\,s$$

$$\sim t_{rise}^{10-90\%} = 2.2\tau \simeq 8.5\ secs.$$

[30%]

Examiner's comment:

A very popular and well answered question. Most candidates could derive the raw signal level under load, and made good attempts at estimating the thermal time-constant of the gauges. However, the offset due to asymmetric thermal coupling was only correctly answered by a few candidates.