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4B13 CRIB 2007

1(a)

$R = 1\,k\Omega$ @ $0°C$ with $\beta' = 3100$

$$R = A e^{\beta'/T} = 1000 = A e^{\frac{3100}{273}}$$

$$\therefore A = 0.0117\ \Omega$$

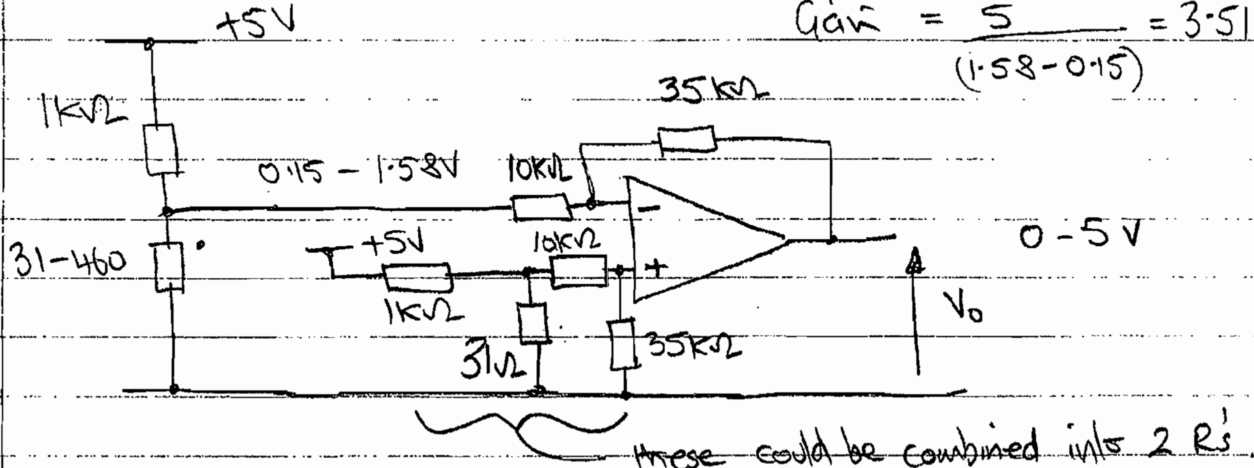
$$R_{20°} = 0.0117\, e^{\frac{3100}{293}} = 460\ \Omega$$

$$R_{120°} = 0.0117\, e^{\frac{3100}{393}} = 31.2\ \Omega$$

Hence connect the thermistor into a potential divider circuit and use an op-amp. to set the gain and offset required.

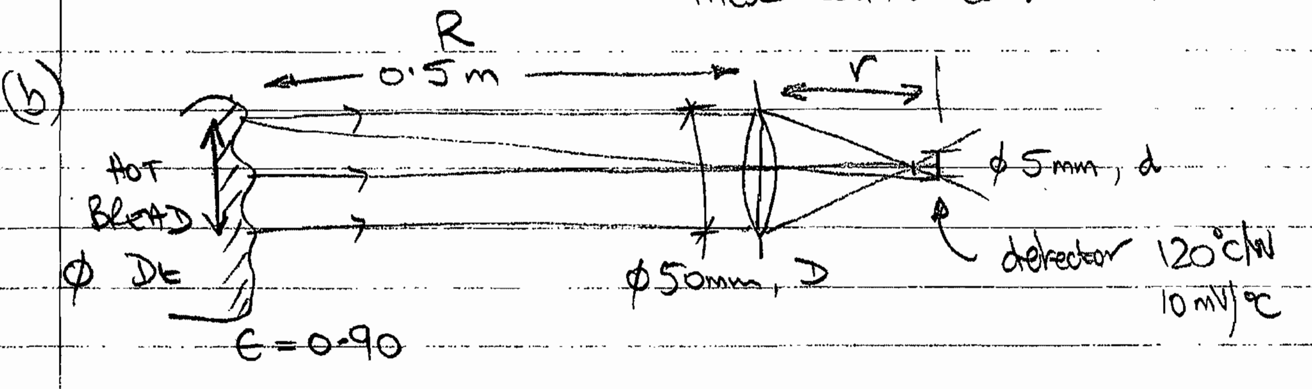
offset = 0.15V

$$\text{Gain} = \frac{5}{(1.58 - 0.15)} = 3.51$$



[35%]

(b)



Heat flux emitted = $\sigma_{SB}\, \epsilon\, T^4$ per unit area. = W

Heat collected by sensor $\delta W = \frac{W A \cos\theta}{\pi} \delta\omega$

where $\delta\omega = \left(\frac{\frac{\pi D^2}{4}}{4\pi R^2}\right) . 4\pi = \frac{\pi D^2}{4R^2}$ sterad.

by similar Δ's, $\frac{D_t}{R} = \frac{d}{r}$ and also $\cos\theta \approx 1$

1(b) contd.

$$\therefore \delta W = \sigma_{SB}\, \epsilon\, T^4 \frac{\pi D_t^2}{4} \frac{\pi D^2}{4R^2} \frac{1}{\pi}$$

$$\delta W = \sigma_{SB}\, \epsilon\, T^4 \frac{\pi}{16}\left(\frac{d}{r}\right)^2 D^2$$

$$\frac{D_t}{R} = \frac{d}{r} = \frac{5}{75} = \frac{D_t}{500} \quad \therefore D_t = 33 \text{ mm } \phi \text{ area on cnst.}$$

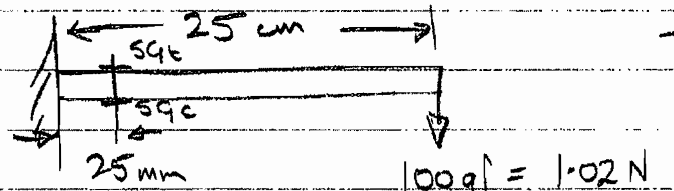
and $\delta W = 5.6\times10^{-8} . 0.9 . T^4 . \frac{\pi}{16} . \left(\frac{5}{75}\right)^2 . (50\times10^{-3})^2 = 11\times10^{-14}\, T^4$

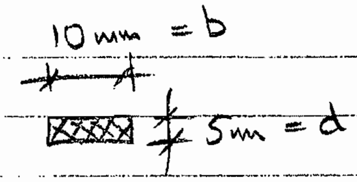
So, @ 120°C, $T = 393\,K \Rightarrow \delta W = 2.62$ mW

130°C, $T = 403\,K \Rightarrow \delta W = 2.90$ mW

[35%] $\therefore$ difference $= 0.28$ mW $\times 120\,°C/W \times 10\,mV/°C \Rightarrow$ 332 μV (0.33 mV)

(c)





$$I = \frac{bd^3}{12} = 1.04\times10^{-10}\ m^4$$

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

$$M = 1.02 \times (250-25)\times10^{-3} = 0.23\ Nm$$

$$\therefore \sigma = 0.23 . \frac{5\times10^{-3}}{2} / 1.04\times10^{-10} = 5.53\times10^{6}\ N/m^2 = \epsilon E$$

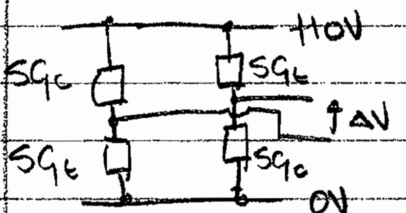
with $E = 195\ GN/m^2 \quad \therefore \epsilon = 0.028\times10^{-3}$

$\therefore$ with a gauge factor $= 2$ and all 4 bridge resistors as active strain gauges,

$$V_o = 2\times0.028\times10^{-3}\times10\,V$$

$$= 0.56\ mV$$

change with 100 gf load.



[30%]

2 a) A transformer bridge has 2 arms made up of carefully made windings and has

(i) No change with temperature of the relative emfs induced in the 2 arms. — so no errors such as temp coefficient

(ii) No changes such as ageing or changes due to humidity these much affect bridges with passive matched components

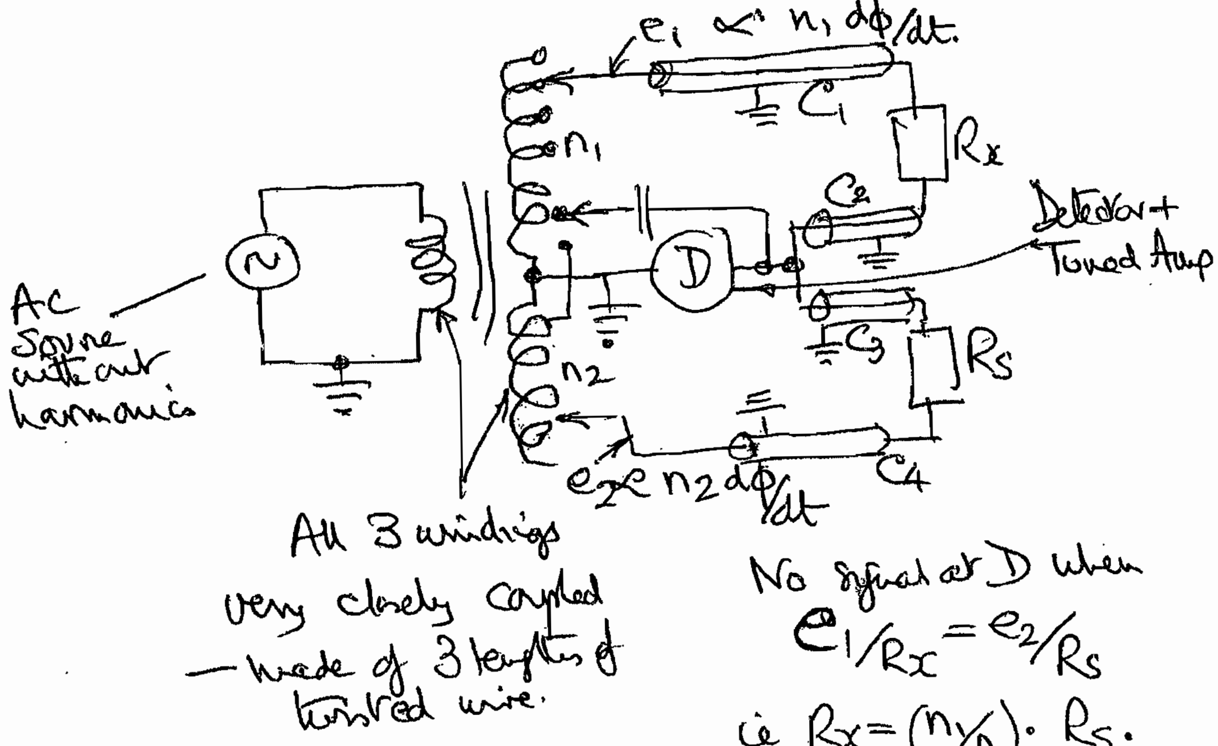
(iii) The emfs induced in the arms will be in the exact proportion to the turns ratio of the windings — a good core material, no saturation and the windings must be v close

(iv) High sensitivity and good rejection of noise is achieved by supplying the bridge with pure sine waves (no harmonics) and using a tuned amplifier to feed the detector

This minimises the power dissipation as emfs → smallish

[15%]

b)



No signal at D when
$$e_1/R_x = e_2/R_s$$
ie $R_x = (n_1/n_2) \cdot R_s$.

Cables C_1 and C_4 only draw extra currents out of windings — these do not go through the detector

Cables C_2 & C_3 have negligible emfs on them at balance — so do not upset currents in R_x and R_s

(Contd)

2 b) continued

One disadvantage is the difficulty of measuring 4 terminal resistors without coaxial construction throughout.

[30%]

(c). Mean of 5 readings = 24.9954 Ω by calculator

Standard Deviation " = 1.82×10^{-3} or 0.0018 Ω.

Standard Uncertainty (5 readings) = $\frac{.0018}{\sqrt{5}}$ = 0.0008 Ω.

So table becomes

Source of Unc'	Value	Prob	K	Std Unc' (U)
Cal of Ref	.0010	Normal	2	.00050
Drift in 2 yrs	.0008	Rect'	$\sqrt{3}$	.00046
Linearity	.0010	Rect	$\sqrt{3}$	.00058
Resolution	.0005	Rect	$\sqrt{3}$	.00029
Power dissipation	.0015	Rect	$\sqrt{3}$	.00087 ← ⊛
Measurement Unc'	→			.00080 ← ⊛

Total Unc = $\sqrt{\text{Sum}(U^2)}$ = 0.0015

and Using K=2, 95% Uncertainty is ±0.0030

As the standard resistor was rising by 0.0020 Ω/year, in the 2 years, it will be .004 more so add this to mean reading.

So Value of new resistor = 24.9994 ± 0.003 Ω

[45%] (uncertainty is quoted with K=2 for a 95% probability)

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d) From the table, 2 uncertainty contributions are bigger: ⊛

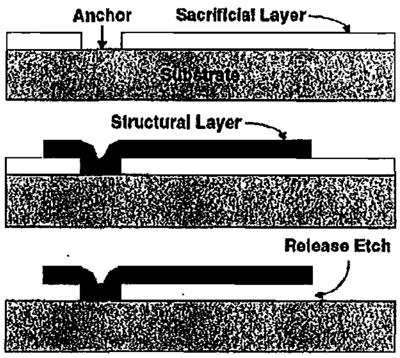
Power Dissipation — so halve this, by suggesting that the bridge is run with 70% of the excitation AC voltage?

Measurement Uncertainty — take more than 5 readings as $\sqrt{\text{No of Readings}}$ is in expression for Standard Uncertainty

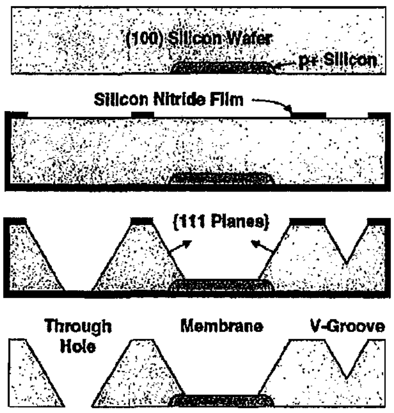
[10%]

3. (a)

Surface micromachining - MEMS structure production by depositing, patterning and etching thin films (<100μm) on top of a substrate. Typically, a sacrificial layer is deposited and patterned, followed by a structural layer which is deposited and patterned, and then the structural layer is released by the etching of the sacrificial layer. EG.



Bulk micromachining – MEMS structure production by the etching of the substrate. Typically, a hard mask (eg. silicon nitride) or other etch stops are used with etching (eg. KOH or deep RIE) in bulk micromachining. EG.



[30%]

(b)

A = anchor = holds the surface structure to the substrate
B = tether/spring = stretches and expands (F=kx) when the structure moves in response to an acceleration.
C = electrodes = used for sense capacitance in determining the displacement of the structure or used in force feedback
D = proof mass = actual mass of the mass-spring system. The holes are to enable the etchant to release the structure from the substrate.

[20%]

3 (c)

- **Open loop** – change in differential capacitance used to determine displacement/acceleration
- **Closed loop** – some of the beam is driven with a voltage to generate a force feedback to counteract the acceleration

[10%]

(d)

There are 30 'fingers' on the proof mass, each 200μm long and 5μm thick.

$$\text{Nominal}\, C = 30\frac{\varepsilon A}{x} = 30\frac{8.9\times10^{-12}\times200\times10^{-6}\times5\times10^{-6}}{0.5\times10^{-6}} = 5.34\times10^{-13}\text{F}$$

Half of the fingers used for sense, other for force feedback.

So $C_{sense} = C_{force} = 2.67 \times 10^{-13}$ F

Assume holes in proof mass cancel the legs & tethers, so :

$vol_{proof} = 100\times10^{-6}\times1000\times10^{-6}\times5\times10^{-6} = 5\times10^{-13}\text{m}^3$

$mass_{proof} = 2300\times5\times10^{-13} = 1.15\times10^{-9}\text{kg}$

1g of acceleration $= 10\ \text{ms}^{-2}$

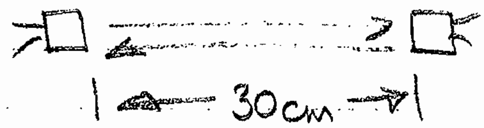
$F = ma = 1.15\times10^{-9}\times10 = 1.15\times10^{-8}\text{N}$

But $F_{electrostatic} = \frac{1}{2}\frac{CV^2}{d}$

$\therefore V = \sqrt{\frac{2Fd}{C}} = \sqrt{\frac{2\times1.15\times10^{-8}\times0.5\times10^{-6}}{2.67\times10^{-13}}} = 0.21\text{V}$ (this is output voltage per g)

[40%]

4(a)



$v = f\lambda \quad \therefore \quad 340 = 120\times10^{3}\lambda \quad \therefore \lambda = 2\cdot83$ mm

Hence, 30 cm = 105·9 wavelengths

$\Delta t = \frac{0\cdot30}{340 \pm 2}$ s = 0·877 to 0·888 ms

$\therefore$ difference = 0·011 ms or 11 μs

11 μs is equivalent to $120\times10^{3} \times 11\times10^{-6}\lambda = 1\cdot32\lambda$

or 475° phase

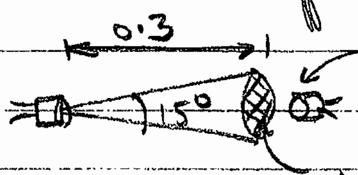
[15%]

(b) Power into transducer $= \left(\frac{9}{2\sqrt{2}}\right)^2 / 500 = 20$ mW $\left(= \frac{V_{rms}^2}{R}\right)$

Power into air $= \frac{15\times20\times10^{-3}}{100} \times \frac{340 \cdot 8\times10^{5} \cdot 4}{(340+8\times10^{5})^2} = 5\cdot1$ μW

* $1\cdot7\times10^{-3}$ power coupling factor

Power received at opposite transducer, with 15° beam angle :-



$A_r = \pi . 0\cdot01^2 = 3\cdot14\times10^{-4}$ m²

$A = \pi\left[0\cdot3 \tan(15/2)^{\circ}\right]^2 = 4\cdot9\times10^{-3}$ m²

$\therefore \quad P_{rec} = 34\times10^{-6} \times \frac{3\cdot14\times10^{-4}}{4\cdot9\times10^{-3}} = 0\cdot33$ μW

$\therefore$ Power coupled into transducer and delivered to a matched load, $P_e = 0\cdot33\times10^{-6} \times 1\cdot7\times10^{-3} \times \frac{15}{100} = 84$ pW

*

$= \frac{V_{rec}^2}{500}$

$\therefore V_{rec} = 0\cdot21$ mV rms

$= 0\cdot58$ mV pp into 500 Ω load

(or 1·16 mV pp into open cct.)

[40%]

4 (c) The snow will have 3 effects

- altered coupling air → snow → transducer + reverse
- attenuation
- smaller air gap (less transit time).

Coupling factor is now:-

air → snow : $\frac{4 . 340 . 500 \times 950}{(340 + 500 \times 950)^2} = 2.86 \times 10^{-3}$ ↑ higher than *

snow → transducer : $\frac{4 . 5 \times 10^5 . 500 \times 950}{(5 \times 10^5 + 500 \times 950)^2} \simeq 1.00$

Attenuation :- 72 dB/m × 2cm = −1.44 dB

thro' 2cm of snow : $P = P_0 10^{-\frac{1.44}{10}} = 0.72 P_0$

∴ net coupling factor $= 2.05 \times 10^{-3}$

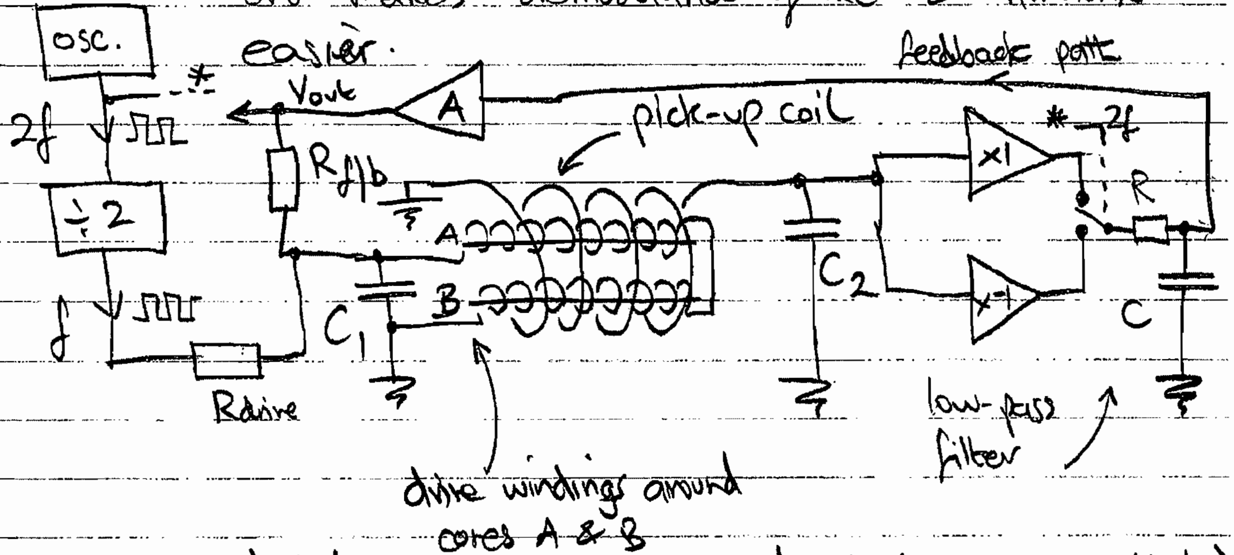
This is an increase of 21%, hence the voltage will increase by $\sqrt{1.21} \simeq 10\%$ increase or ×1.1

The calibration will change as the effective path length is $(30-2) + \left(2 . \frac{340}{950}\right)$ cm = 28.7 cm

or a reduction in transit times of just over 4%.

[45%] ∴ the system will under-read by 4%.

5 (a) Flux-gate principle: a high permeability, low loss magnetic core is surrounded by one or more coils. An applied alternating current drives the core into non-linear (saturation) regions of alternating polarity. The flux changes are detected by a pick-up coil wound around the core – inducing +ve and -ve pulses in it. If an external magnetic field also couples into the core, the temporal symmetry of +ve and -ve pulses is disturbed leading to the introduction of even harmonics (usually the 2^{nd} is largest) into the pick-up coil waveform. A detector circuit eg: a mixer or switched amplifier can detect this 2^{nd} harmonic current and demodulate it to provide a feedback signal (current) opposing the coupled magnetic field – ie: a null feedback system. A pair of cores driven in anti-phase removes the odd harmonics and makes demodulation of the 2^{nd} harmonic easier.



(optional C_1 & C_2 selected to resonant the coils at f & 2f respectively)

It is also possible to use the system without feedback, in open-loop mode: it is simpler but has a less linear response.

Advantages: high sensitivity, low drift, low noise, high linearity

[25%] Disadvantages: complexity of AC circuits, high cost

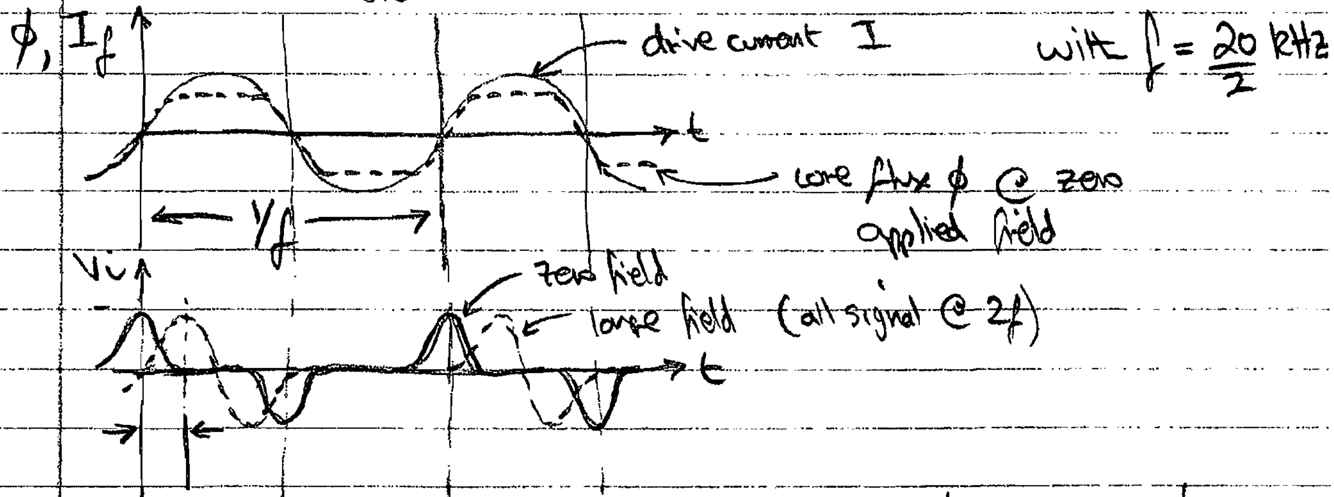
5(b) Core cross-sectional area $= \frac{\pi d^2}{4} = 7.85 \times 10^{-7}\ m^2 = A_{core}$

μ_{eff}, effective rel. permeability $= 1/D = \left(\frac{L}{d}\right)^2 \left[\ln(2L/d) - 1\right]^{-1}$

with $L/d = 30$, $\mu_{eff} = 291$

Core flux, $\phi = B_{core} \cdot A_{core} = \underbrace{100 \times 10^{-6}}_{B_0} \cdot \underbrace{291}_{\mu_{eff}} \cdot \underbrace{7.85 \times 10^{-7}}_{A_{core}} = 2.2 \times 10^{-8}$ Wb

The induced voltage V_i in the pick-up coil is given by
$V_i = N \frac{d\phi}{dt}$ with $N = 200$

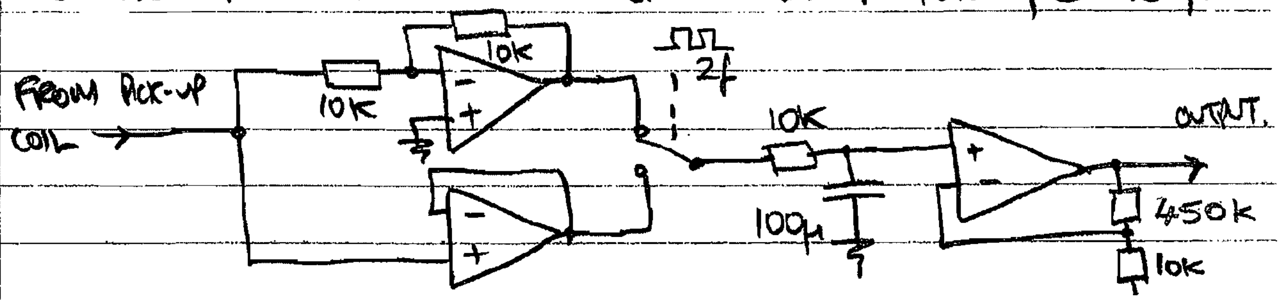


$\frac{1}{8f}$ Assuming the core to be swept in/out of saturation in $1/8f$ seconds

Then $V_i \approx 200 \cdot 2.2 \times 10^{-8} \cdot 8 \cdot 10 \times 10^3 = 0.35\ V$
The 2f switch and RC filter smoothing will average this by a factor of $\frac{1}{\pi}$ (or $\frac{2}{\pi}$ if twin cores used)

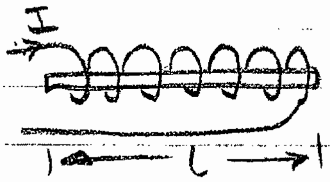
Hence for 5V output, we need a gain of $5 / \frac{0.35}{\pi} = 45$

Choose RC = 1 sec. time constant $\therefore$ R = 10kΩ, C = 100μF



[55%]

5(c) Consider coil with core inside



$l = 30\text{ mm}$
$d = 1\text{ mm}$

$$H \text{ inside coil} = \frac{NI}{l}$$

$$B_{core} = \mu_0 \mu_{eff} H = \mu_0 \mu_{eff} \frac{NI}{l}$$

$$\phi_{core} = B_{core} \cdot A_{core} = \mu_0 \mu_{eff} \frac{NI\pi d^2}{4l}$$

$$L = \frac{N\phi_{core}}{I} = \frac{\mu_0 \mu_{eff} N^2 \pi d^2}{4l}$$

$$= \frac{4\pi \times 10^{-7} . 291 . 200^2 . \pi . 10^{-6}}{4 . 30 \times 10^{-3}}$$

[20%] $\therefore$ $L = 0{\cdot}38\text{ mH}$

ENGINEERING TRIPOS PART IIB 2007

Module 4B13, Electronic Sensors & Instrumentation – Assessor's Report

Q1. Temperature & strain sensors

This was a fairly popular question and generally quite well attempted. Most candidates knew the characteristics of thermistors and the pyrometer system analysis was generally along the right lines, although a few candidates assumed the heat source to be an isotropic rather than Lambertian radiator. The final part on strain gauges was not generally well done.

Q2. Transformer bridge

This was not a very popular question but was quite well answered by those who did attempt it. Most candidates could draw the bridge schematic and knew how it worked in principle but were less clear on its advantages and disadvantages. The expanded uncertainty table was not fully correctly completed in most cases.

Q3. MEMs accelerometer

A very popular and straightforward question, which was well answered in the majority of cases. The process description parts were well recalled by most candidates and the dimensional assumptions made in the final part to calculate the response of the sensor illustrated were generally reasonable.

Q4. Ultrasonic sensor system

This was also a fairly popular question attracting a wide range of attempts. The first part was quite straightforward and most candidates managed to work out the time delay, but not the equivalent phase shift. Most attempts at calculating the signal levels followed the correct method although a few candidates did not use the beam angle data correctly. The final part concerning snow coverage was counter-intuitive and only a few candidates arrived at the correct solution.

Q5. Fluxgate magnetic sensor

Another less popular question where the attempts tended to fall into 2 categories – those that knew it well and those who did partial attempts, presumably as a last resort. There were a few very good answers to the system description and design parts although nobody correctly calculated the self inductance of the sensor, even though this should have been fairly straightforward.

Dr P.A. Robertson, May 2007