IMPERIAL COLLEGE LONDON

DEPARTMENT OF ELECTRICAL AND ELECTRONIC ENGINEERING
EXAMINATIONS 2013

EEE/EIE PART III/IV: MEng, Beng and ACGI

BIOMEDICAL ELECTRONICS

Friday, 18 January 10:00 am

Time allowed: 3:00 hours

There are SIX questions on this paper.

Answer FOUR questions.

All questions carry equal marks.

Any special instructions for invigilators and information for candidates are on page 1.

Examiners responsible First Marker(s) : P. Georgiou
Second Marker(s) : C. Papavassiliou

1. This question relates to the design of an instrument for measuring biopotentials.

a) Explain how an action potential is generated referring to the ionic flow of sodium and potassium ions. [4]

b) Table 1.1 lists five commonly observed bio-potentials and their amplitude and frequency characteristics. A doctor requires an instrumentation system to record activity from the muscles from a paralysed patient. The front end will use the instrumentation amplifier shown in Figure 1.1

(i) Derive an expression for the output voltage V_{out} of the amplifier as a function of the differential voltage V_1-V_2 and select suitable resistor values to give you a gain of -11. You may use R_2=100KΩ. [4]

(ii) Design a suitable band pass filter to extract the signal of interest. You may assume a 20dB/decade roll off for both the low-pass and the high pass sections. State equations for cut off frequencies and select suitable resistors. You may assume you have 10nF capacitors to your disposal. [4]

(iii) The instrumentation system will work off a 6 V coin cell battery. Using the circuits of parts b.i, and ii and any additional circuits, sketch the complete schematic of the instrumentation system which utilises the whole dynamic range of the system. Annotate on your schematic values of resistors and capacitors with a justification of the final choices. You may assume V_{DD}=3V and GND=0V and V_{SS}=-3V. [4]

c) The doctor checks his electrodes and finds that when connected, the electrode tissue interface impedance is 10MΩ. Calculate the minimum input impedance of the instrumentation amplifier Figure 1.1 that will guarantee an attenuation of less than 10% of the sensed bio-potential voltage. [4]

Table 1.1

Signal	Frequency range (Hz)	Amplitude range (mV)
ECG	0.1 – 300	0.05 – 3
EEG	0.5 – 40	0.001 – 1
EMG	20 – 2000	0.001 – 100
Neural Spikes	300-5000	0.001– 0.5
Local Field Potentials	10-200	0.001 – 5

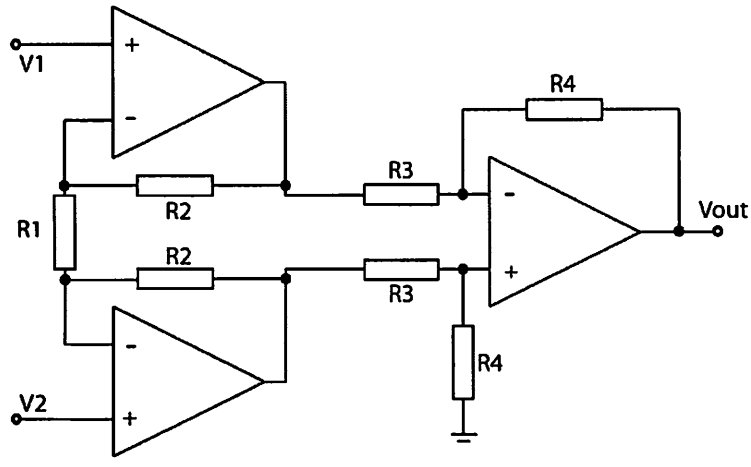


Figure 1.1

2. This question relates to the design of an electrical stimulation circuit for a neural prostheses.

a) Sketch an asymmetric biphasic waveform (i.e. current vs. time) with a 50μs interphasic interval to deliver a stimulus of 40nC given the cathodic/anodic ratio is 4:1 and the maximum allowable current is 0.4mA. [3]

b) What is the purpose of implementing an asymmetric waveform with the interphasic interval ? [3]

c) Design (i.e. draw a logic circuit for) a finite state machine (FSM) to produce the appropriate control signals for generating the waveform in your answer to part (a) based on the circuit given in Figure 2.1 Sketch the timing diagram for signals P1, P2, P3 and P4. [8]

d) The manufacturer of the current source chips (i.e. components X1 and X2 in Figure 2.1) quote a tolerance of 0.1% on the accuracy of the current magnitude. Discuss the impact of this on the electrical neural stimulator design. How can this be overcome? [3]

e) Explain why current-mode stimulus generation often requires a relatively large voltage headroom. [3]

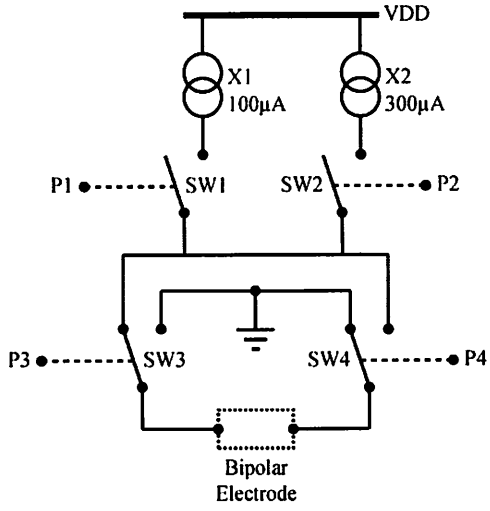


Figure 2.1

3. This question relates to the design of chemical sensor instrumentation.

a) State two types of electrochemical measurement explaining the principle of operation of each. [4]

b) A glucose sensor has been fabricated with a circular disc working electrode shown in Figure 3.1. The radius of the disc, r=0.1mm. The electrode is coated with glucose oxidase to give a peak current to glucose at V_{Cell}=0.7 V according to the following reaction:

$$\text{glucose} + O_2 \xrightarrow{\text{glusoce oxidase}} \text{gluconic acid} + H_2O_2 \quad (1)$$

$$H_2O_2 \rightarrow O_2 + 2H^+ + 2e^-$$

(i) Calculate using equation 2 below the peak redox current for the reaction above for a glucose concentration of C=20mM. You may assume the number of electrons n is solely given by the oxidation of H_2O_2 and the diffusion coefficient D=4.38X10^{-8} m^2/s. [2]

$$i_p = 2.69 \times 10^5 n^{3/2} A D^{1/2} C \quad (2)$$

(ii) Draw a circuit schematic of a suitable potentiostat to drive the electrochemical cell shown in Figure 3.1. [2]

(iii) Using the results from b.i, design a system comprising of a potentiostat, a transimpedance amplifier and a resistor that will operate the sensor in Figure 3.1 using a single 3V supply. Choose a suitable resistor value for the transimpedance amplifier which utilises the full dynamic range of the system at a glucose concentration of 20mM. Annotate clearly the values of any input and output voltages. [6]

(iv) State one limitation of your design which would prevent implementation in a full custom CMOS ASIC. [2]

c) Sketch the schematic of an alternative transimpedance amplifier that uses no resistors and can be implemented in CMOS. Explain its operation and justify why it is a suitable alternative. [4]

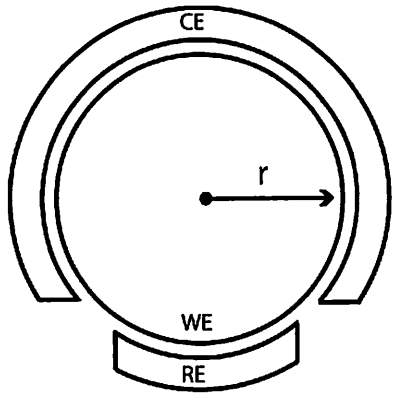


Figure 3.1

4. This question concerns thermal and kinetic energy harvesting power supplies for powering body worn and implanted medical electronics.

a) (i) A thermal energy harvester is worn by a patient on the chest with good thermal contact to the skin. The thermal resistance between the core of the body and the skin is 0.05 m^2K/W when at rest. Estimate the absolute maximum power that could be generated by a thermoelectric generator with a skin contact area 1 cm^2 when the patient is resting indoors.

[3]

(ii) Why will a real generator produce less power than this?

[2]

b) (i) Explain the difference between the two main categories of motion-driven energy harvester (one of which is shown in Figure 4.1) and how they might be applied in the human body. Discuss the advantages and disadvantages of each.

[5]

(ii) From first principles, show that the power generated by the inertial energy harvester drawn in Figure 4.1 can be written as:

$$P = \frac{\zeta m Y_0^2 \omega^3 \omega_c^3}{\left[1-\omega_c^2\right]^2 - \left[2\zeta\omega_c\right]^2}$$

Where $\zeta=D/(2m\omega_n)$, $\omega_c=\omega/\omega_n$ and ω_n is the undamped resonant frequency of the mass and spring. The mass has value m and the spring has a constant of k. The system is driven at an angular frequency ω with frame amplitude of Y_0.

[5]

c) The power output of an energy harvester operating at resonance can be simplified to:

$$P_{res} = \frac{1}{2} Y_0^2 \omega^3 m Z_l$$

where Z_l is the displacement limited amplitude of the mass travel. For a harvester with its mass constrained to move in a volume, as shown in Figure 4.2, show that in an optimal configuration, the mass occupies half the swept volume, *i.e.* $L_m=L_c/2$. The cross sectional area of the volume is A.

[5]

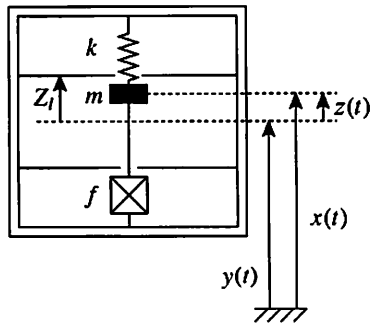


Figure 4.1 Motion-Driven Energy Harvester

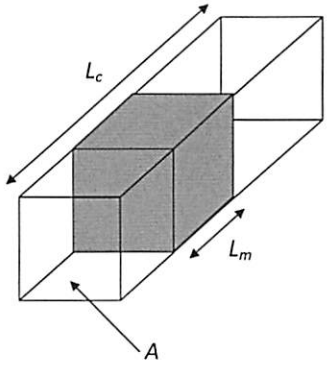


Figure 4.2 Energy harvester with constrained mass motion

5. This question relates to the design of an implantable brain machine interface (BMI) that will use a transcutaneous link for transmitting data both into and out of the body.

a) (i) Sketch a block diagram of an appropriate transcutaneous link, including all main components (at block-level). [4]

(ii) Briefly describe two challenges of using this type of communication link for this specific application stating any practical implications. [2]

b) The transmitted data (from implant to external device) will be encoded using Binary Frequency Shift Keying (BFSK). Sketch the modulated signal encoding the binary sequence 00101000 using this scheme. [2]

c) It is proposed to use an optical telemetry for the downlink. State two fundamental properties of optical transmission (in a medium) that would degrade performance? [2]

The function of this BMI is to record extracellular action potentials from a microelectrode array. Assuming that each channel will record spikes from at most three different neurons, and that these spikes will have distinct features (example spikes shown in Figure 5.1), it is required to classify the spikes (i.e. being able to identify which spike shape is being recorded).

d) Sketch a typical block diagram for classifying these spikes (after amplification and filtering). [3]

e) To reduce the communication bandwidth (i.e. data rate), it is proposed to extract specific features from each spike recorded and transmit only these, instead of the entire raw signal. Identify two different features that could be used to distinguish between different spike shapes (for spike sorting)? [2]

f) Sketch a flow chart for detecting and extracting one of the features identified previously in your answer to part (e). Given that the positive spike peaks (shown in Figure 5.1) vary from 0.75±0.25mV, and negative peaks vary from -0.75±0.25mV, estimate the range and resolution required to represent the feature selected. State any assumptions made. [5]

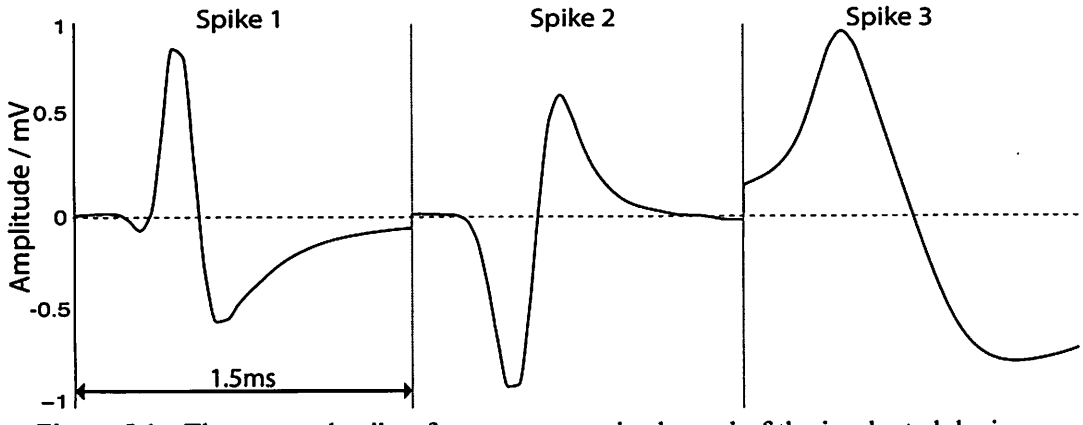


Figure 5.1 - Three neural spikes from one example channel of the implanted device.

6. This question relates to an implantable Brain Machine Interface (BMI) for motor control.

The front-end architecture of a single channel is shown in Figure 6.1. This has been designed to interface with a multi-electrode array to observe **only** the *Extracellular Action Potentials (EAPs)* and **not** the *Local Field Potentials (LFPs)*. The front-end includes a front-end bio-potential amplifier (A1), a bandpass filter (to reject the LFPs), a second amplification stage (A2) and an Analogue to Digital Converter (ADC) to digitize the signal.

a) Given the signal characteristics and circuit constraints detailed in Figure 6.1, determine the appropriate values for the gains (A1 and A2) and the ADC Resolution (X) and the Sampling rate (Y). State any assumptions made. [6]

b) If the system is to utilize a transcutaneous biotelemetry (for data output) with a 10Mbit/s data-rate, calculate how many channels can be supported (based on your answer to part (a)). [2]

c) Detail how the system could be modified to support a higher channel count (for the 10Mbit/s data rate) given that the features of interest are the EAP spike shapes and inter-spike intervals. Your answer should include a block-level diagram in describing the amended system. [7]

d) State three reasons why it is *essential* for such a system to have low power consumption. [3]

e) If such a device was to be submitted for regulatory approval to the MHRA (in the UK), how would this be classified and why? What is the equivalent regulatory body in the USA (i.e. to the MHRA)? [2]

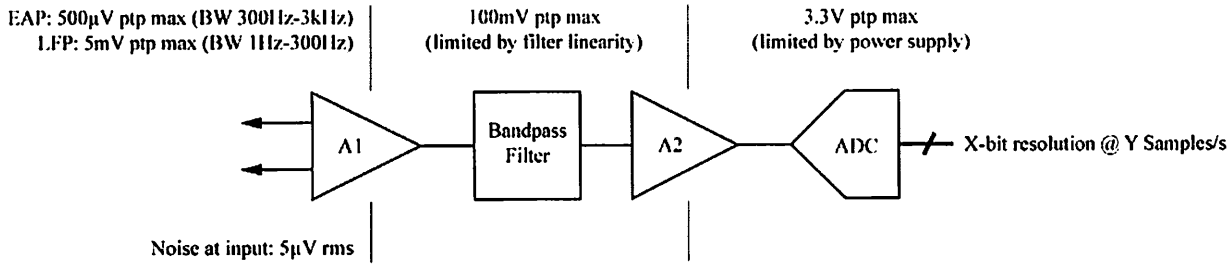


Figure 6.1

Biomedical Electronics

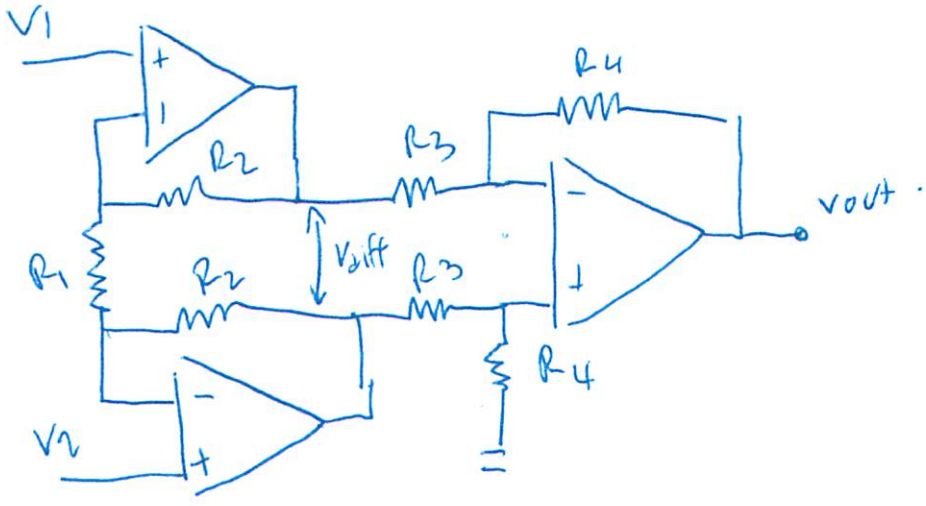
Solutions 2013

[4]

1.a) Bookwork.

b) i) Muscles refer to EMG. $f_L = 20Hz$, $f_H = 2000Hz$

$V_{min} = 0.001mV$, $V_{max} = 100mV$.



$$V_{diff} = \frac{(R_1 + 2R_2)(V_1 - V_2)}{R_1}$$ [2/4]

$$= (V_1 - V_2)(1 + 2R_2/R_1).$$

$$V_{out} = -V_{diff}\frac{R_4}{R_3}.$$

$$V_{out} = -(V_1 - V_2)(1 + 2R_2/R_1)\,R_4/R_3.$$

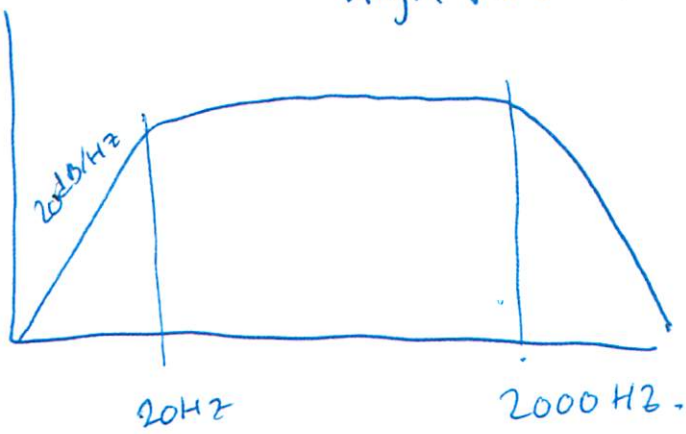
Set $R_4 = R_3 = 100k\Omega$.

$R_2 = 100k\Omega$.

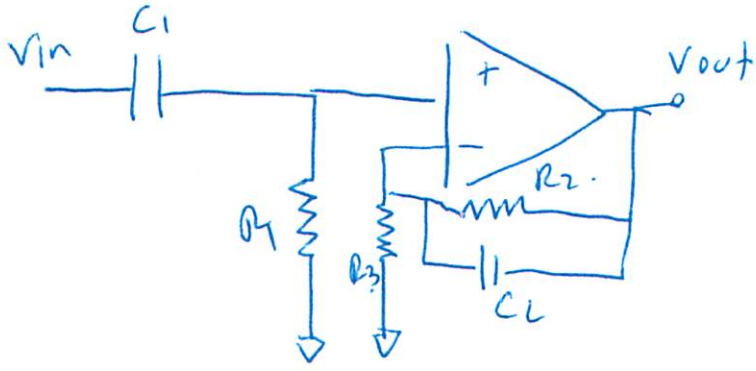
$$\text{Gain} = 1 + \frac{200k}{R_1} = 11.$$ [2/4]

$R_1 = 20k\Omega$

ii) Spectrum 20dB roll off means first order high pass and low pass sections.



Circuit:



$f_L = 20Hz = \frac{1}{2\pi R_1 C_1}$, with $C_1 = 10nF$ [2/4]

$R = 796k\Omega$.

$f_H = 2000Hz = \frac{1}{2\pi R_2 C_2}$, with $C_2 = 10nF$. [2/4]

$R_2 = 7.96k\Omega$.

$R_3 = 7.96k\Omega$ to give a gain of 0dB.

iii). 6V supply means $V_{max\,pp} = 6V$.

$V_{max} = 100mV$ of EMG.

First stage Gain = 11.

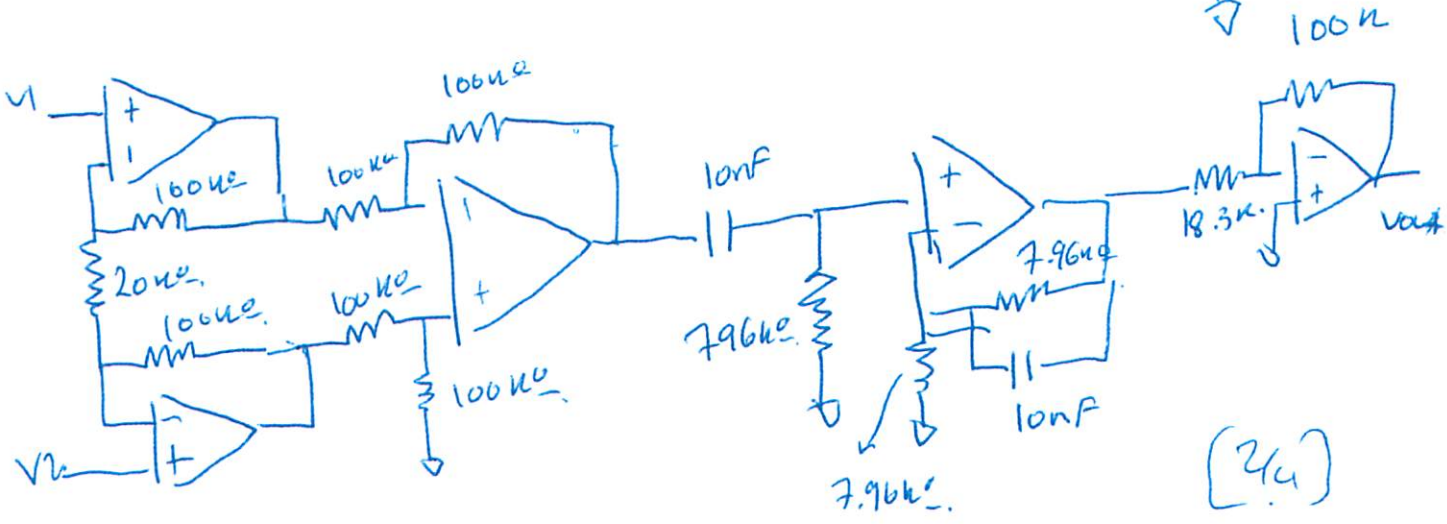
Second Stage filter gain = 1.

Signal output of filter $V_{sig} = 100mV \times 11 = 1.1V$.

To occupy 6V of headroom [2/4]

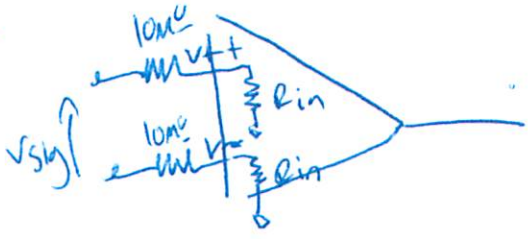
Gain of final stage = $\frac{6V}{1.1V} = 5.45$

Complete System



[2/4]

c).



$$(V_+ - V_-) = \frac{V_{sig} \cdot R_{in}}{10M\Omega + R_{in}}$$

[2/2]

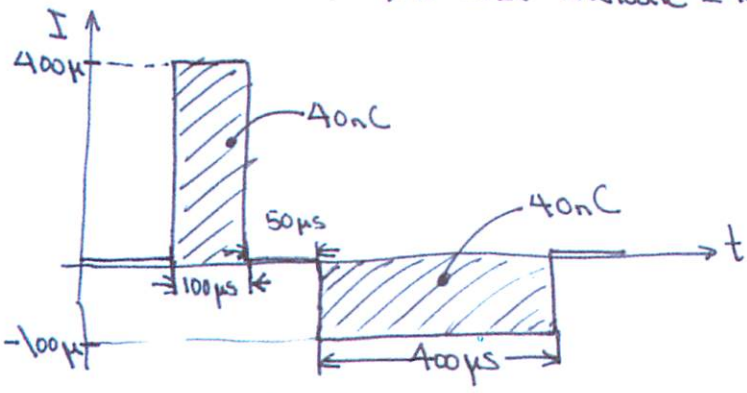
Less than 10% attenuation means $\frac{(V_+ - V_-)}{V_{sig}} = 0.9$

$$0.9 = \frac{R_{in}}{10M\Omega + R_{in}} \Rightarrow R_{in} = 90M\Omega$$ Guarantees this. [2/4]

(2) Stimulation question.

(a) - 50μs interphasic interval
- 40nC target charge
- $I_{max} = 0.4mA$
- cathodic : anodic ratio = 4:1

$\therefore I_{cathodic} = 400\mu A$ and $I_{anodic} = 100\mu A$



not to scale (diagram)[2]

$$t_{cathodic} = \frac{40nC}{0.4mA} = 100\mu s$$

$\therefore t_{anodic} = 4 \times t_{cathodic} = 400\mu s$ (values)[1]

(b) The assymetric waveform is used to reduce fatigue in neural tissue → ie. cathodic phase at high amplitude (short duration) to activate and anodic phase at lower amplitude (longer duration) to charge balance [2]

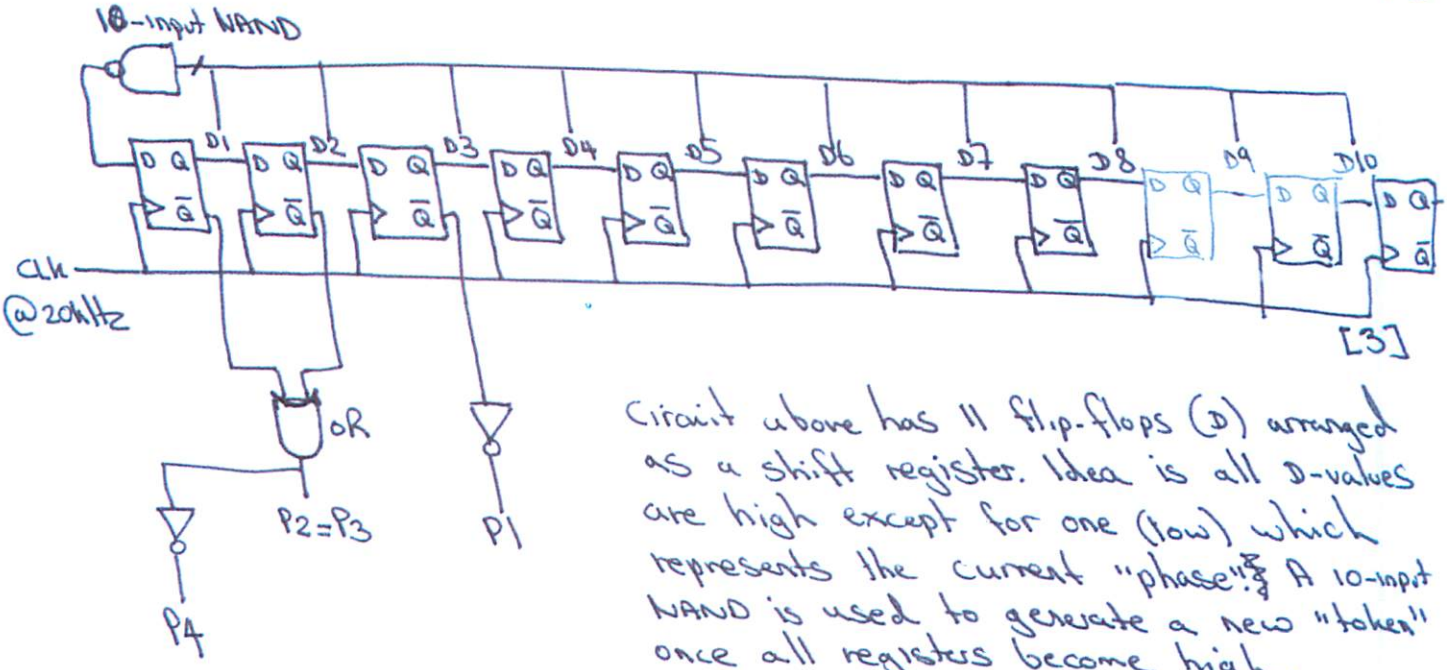
The interphasic interval is used to avoid the anodic phase acting to "block" the activation. This can occur if one phase closely follows the other (under certain conditions). [1]

(c)

[2]

To produce desired waveform need 11 clock phases at 50μs each.
∴ Need 20kHz clock.

Can either implement using flip-flops (token-approach) or counter → flip-flop approach shown below: [1]



[3]

Circuit above has 11 flip-flops (D) arranged as a shift register. Idea is all D-values are high except for one (low) which represents the current "phase". A 10-input NAND is used to generate a new "token" once all registers become high.

This circuit will continually stimulate at a rate of $\frac{1}{850\mu s} = 1.18kHz$

→ can also be made "one-shot"

(d) A 0.1% tolerance on current magnitude means the anodic and cathodic current ratio may not be precisely 4. ① [2]

Eg. if 100μA is -0.1% and 300μA is +0.1%

⇒ ratio is: 4.006 instead of 4. ①

This will result in a charge imbalance after each stimulation cycle – i.e. anodic and cathodic charge not precisely equal.

This can be overcome by shorting the electrodes together (or to ground) after each few stimulation cycles. ① [3]

(e) Current-mode stimulus generation generally requires large headroom to allow for tuneability of the stimulus magnitude given a nominal electrode impedance (or range). For example, for a 10kΩ electrode, generating a current between 100μA → 1mA would require a 10V supply in addition to minimum requirement for current output stage (typically 1 × V_{DS} if single MOSFET o/p)

[3]

3. a) Bookwork. describe amperometry and potentiometry. (2/4) (2/4)

b) Student must realise disc area is πr^2 and solve for WE current:

i) $i_p = 2.69 \times 10^5 \, n^{3/2} A . D^{1/2} . C$.

$n = 2$.

$D = 4.38 \times 10^{-8}$

$C = 20mM = 20 \times 10^{-3}$ M.

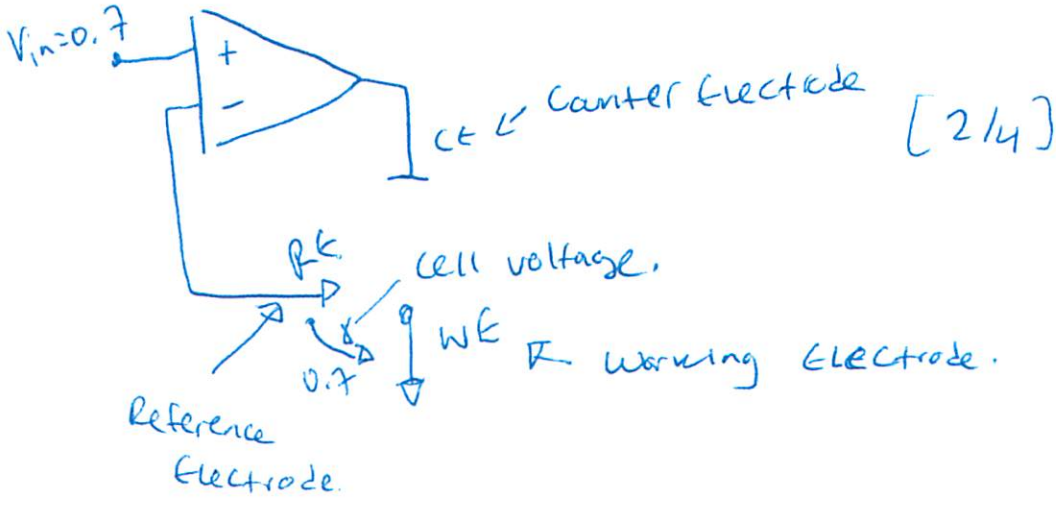
$r = 0.1mm = 0.1 \times 10^{-3}$

$A = \pi r^2 = 3.14 \times (0.1 \times 10^{-3})^2 = 3.14 \times 10^{-8}$

$i_p = 2.69 \times 10^5 \times 2^{1.5} \times 3.14 \times 10^{-8} \times 4.38 \times 10^{-4} \times 20 \times 10^{-3}$

$i_p = 2.09 \times 10^{-7} = 209 nA.$ (2/4)

ii).

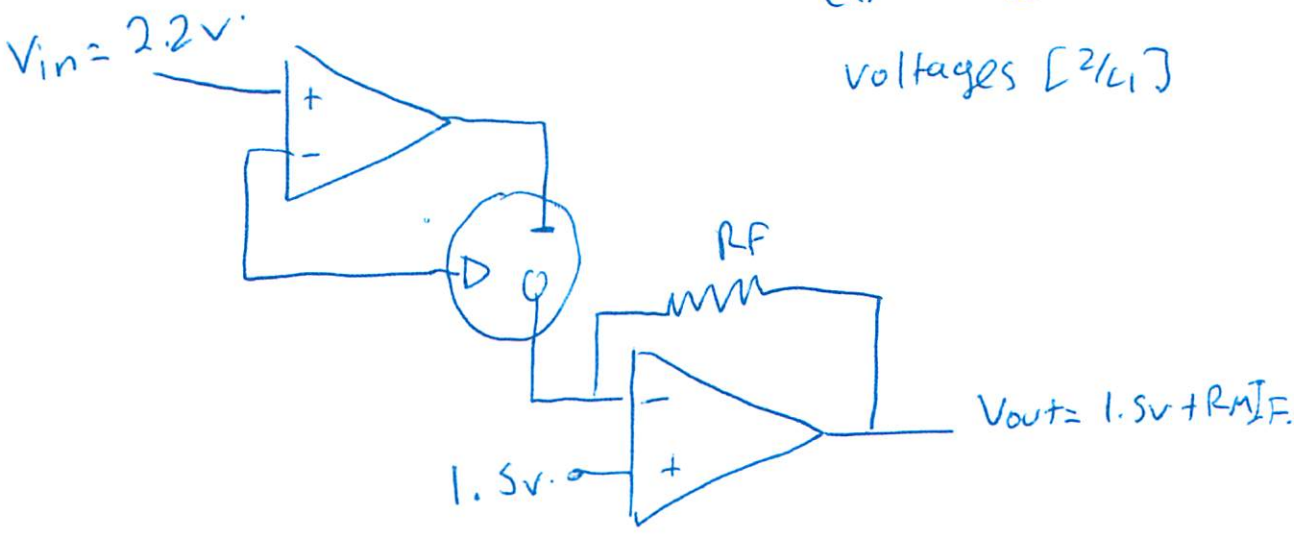


[2/4]

iii)

circuit [2/4]

voltages [2/4]



$V_{out} = 1.5V + R_M I_F$

At 20mM $I_F = 209\,mA$.

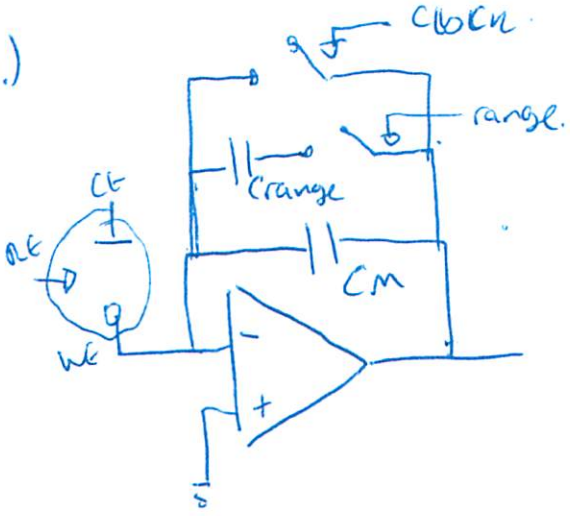
For full utilisation of dynamic range $V_{out} = 3V$ at 209mA.

$3V = 1.5V + R_M \times 209\,nA.$

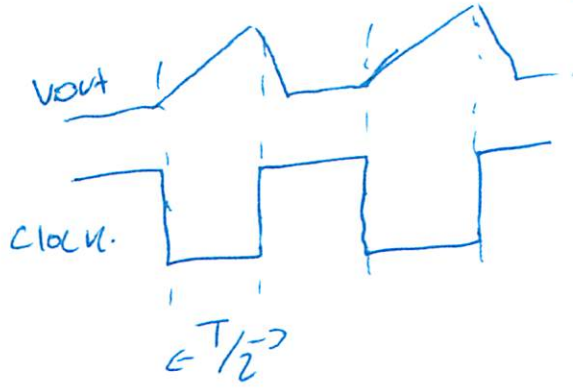
$R_M = \frac{1.5}{209nA} = 7.17\,M\Omega.$ [2/4]

iv) Implementing big resistors is generally difficult in CMOS as they consume a lot of area. [2/2]

d.)



Switched capacitor circuit (2/4)



$V_{out} = 2f(T/2C_M)$

Output voltage is proportional to the period. [2/4]

So we can realise a larger resistor by having a long period or a small capacitor C_M

Questions and Answers

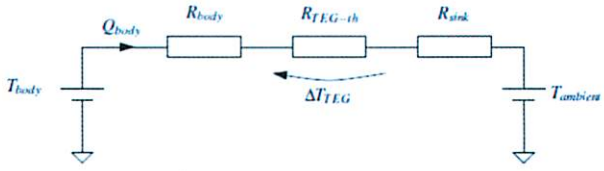
4. This question concerns thermal and kinetic energy harvesting power supplies for powering body worn and implanted medical electronics.

a)

i) A thermal energy harvester is worn by a patient on the chest with good thermal contact to the skin. The thermal resistance between the core of the body and the skin is 0.05 m^2K/W when at rest. Estimate the absolute maximum power that could be generated by a thermoelectric generator with a skin contact area 1 cm^2 when the patient is resting indoors.

[3]

[straight-forward calculation]
The core temperature of the human body is ~37°C and a typical indoor temperature is 21°C . Thus, we have a thermal circuit from core to ambient, through the thermoelectric generator (TEG) as follows:



Consequently, for maximum power from the body into the TEG requires the thermal resistance of the TEG to be matched to that of the body and the heat sink to ambient thermal resistance to be minimised.

Over a 1 cm area, the thermal resistance from core to skin is 500K/W. This means the total power flow through the harvester is:

*P=(37-21)/(2*500)=16 mW*

Only half of this can be extracted from the resistive output TEG, making 8 mW maximum electrical power.

ii) Why will a real generator produce less power than this?

[2]

[Application of knowledge of materials]
There are several reasons possible here, including:

- *The heat sink will not be perfect and will exhibit a temperature drop between itself and the air*
- *There is some contact resistance between the generator and skin and TEG and heat sink*
- *The efficiency of the TEG is somewhat lower than 1, typically 1%, meaning on only 1% of the heat energy is converted into an electrical form.*

b)

i) Explain the difference between the two main categories of motion-driven energy harvester (one of which is shown in Figure 1) and how they might be applied in the human body. Discuss the advantages and disadvantages of each.

[5]

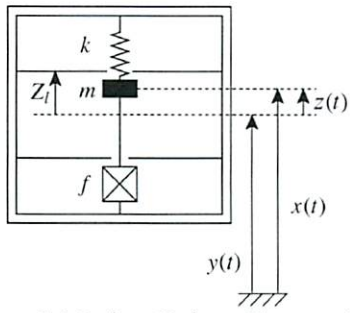


Figure 1 Motion-Driven Energy Harvester

[bookwork]
1 mark per point, including, but not limited to:

- *The two types of motion-driven harvester are inertial and direct-force.*
- *The direct-force type harvester requires two attachment points, i.e. mechanical work is done by moving the two "ends" of the harvester relative to each other.*
- *The inertial harvester is self-contained and only requires 1 attachment point*
- *Inertial devices are thus easier to install and hermetically seal than direct force*
- *Direct-force devices tend to have higher power densities than the inertial type*

ii) From first principles, show that the power generated by the inertial energy harvester drawn in **Error! Reference source not found.** can be written as:

$$P = \frac{\zeta m Y_0^{\,2} \omega^3 \omega_c^{\,3}}{\left[1-\omega_c^{\,2}\right]^2 - \left[2\zeta\omega_c\right]^2}$$

Where $\zeta = D/(2m\omega_n)$, $\omega_c = \omega/\omega_n$ and ω_n is the undamped resonant frequency of the mass and spring. The mass has value m and the spring has a constant of k. The system is driven at an angular frequency ω with frame amplitude of Y_0.

[5]

[Bookwork]
The equation of motion for the mass with respect to the frame is given by:

$$m\ddot{z}(t) = -kz(t) - D\dot{z}(t) - m\ddot{y}(t)$$

And so the transfer function between Z(s) and Y(s) is:

$$\frac{Z(s)}{Y(s)} = \frac{-s^2}{s^2 + 2\zeta\omega_n s + \omega_n^{\,2}}$$

[3-21]

The amplitude of the transfer function is:

$$\frac{Z_0}{Y_0} = \frac{\omega_c^{\ 2}}{\sqrt{\left(1-\omega_c^{\ 2}\right)^2 + \left(2\xi\omega_c\right)^2}}$$

[3]

Thus the velocity of the mass relative to the frame is sinusoidal with amplitude

$$\dot{Z}_0 = \frac{Y_0\omega\omega_c^{\ 2}}{\sqrt{\left(1-\omega_c^{\ 2}\right)^2 + \left(2\xi\omega_c\right)^2}}$$

As the power dissipated in the damper is:

$$E = 2D\int_{-Z0}^{Z0}\dot{z}dz$$

The power simplifies to:

$$P = \frac{\xi m Y_0^{\ 2}\omega^3\omega_c^{\ 3}}{\left[1-\omega_c^{\ 2}\right]^2 + \left[2\xi\omega_c\right]^2}$$

[2]

c) The power output of an energy harvester operating at resonance can be simplified to:

$$P_{res} = \frac{1}{2}Y_0^{\ 2}\omega^3 m Z_l$$

where Z_l is the displacement limited amplitude of the mass travel. For a harvester with its mass constrained to move in a volume, as shown in Figure 2, show that in an optimal configuration, the mass occupies half the swept volume, *i.e.* L_m=L_c/2. The cross sectional area of the volume is A.

[5]

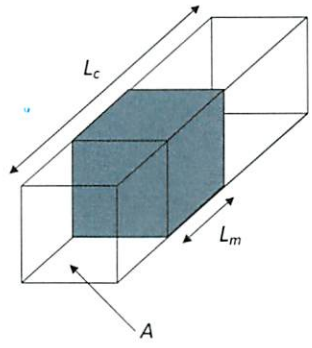


Figure 2 Energy harvester with constrained mass motion

[new calculation]

The mass can be written as

$$m = \rho A L_m$$

The maximum amplitude of displacement, Z_l is given by:

$$Z_l = \frac{L_c - L_m}{2}$$

Substituting m and Z_l into the formula given, we obtain:

$$P_{res} = \frac{1}{4} Y_0^{\,2} \omega^3 \rho A L_m \left(\frac{L_c - L_m}{2} \right)$$

Therefore:

$$\frac{dP_{res}}{dL_m} = \frac{1}{4} Y_0^{\,2} \omega^3 \rho A \left(L_c - 2L_m \right)$$

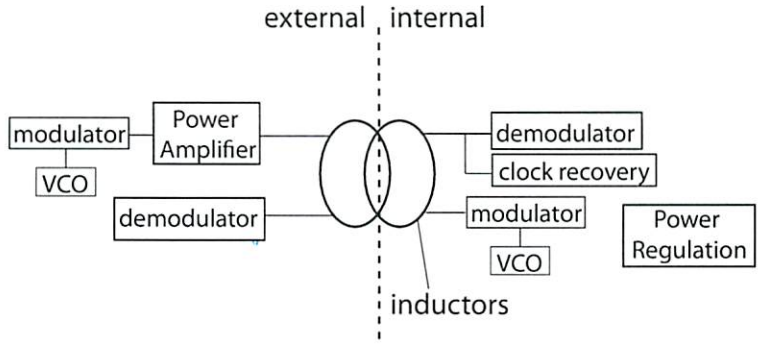
Which is equal to zero when $L_m = L_c/2$, i.e. the mass occupies half the swept volume. Hence this maximises the power. The student should also take the second derivative to show this is indeed a maximum.

5. This question relates to the design of an implantable brain machine interface (BMI) that will use a transcutaneous link for transmitting data both into and out of the body.

a) (i) Sketch a block diagram of an appropriate transcutaneous link showing both the implanted and external devices, including all main components (at block-level). [4]

Can include:

1. Internal and external inductors [1]
2. Power Amplifier on external or at least side [1]
3. Modulators and demodulator block labeled with voltage-controlled oscillator (VCO) on both sides of the system (as hinted by question) [1]
4. Clock Recovery [1]



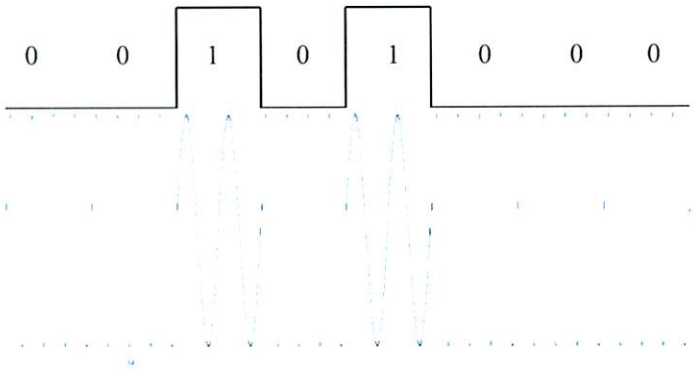
(ii) Briefly describe two challenges of using this type of communication link for this specific application stating any practical implications. [2]

Possible answers, any of which will be allocated marks:

1. Challenge: Size of inductors; Effect: limited area of implant device or transmission frequency/power [1]
2. Challenge: Alignment of Inductors; Effect: reduced linkage therefore more power needed [1]
3. Challenge: Thermal/hear dissipation due to current in inductor coils; Effect: can cause tissue damage if raised 1 degree centigrade [1]

b) The transmitted data (from implant to external device) will be encoded using Binary Frequency Shift Keying (BFSK). Sketch the modulated signal encoding the binary sequence 00101000 using this scheme. [2]

Should show a sine wave that changes frequency during a binary 1 [1]
Sine wave should be half or double the frequency during the binary 1 [1]



c) It is proposed to use an optical telemetry for the downlink. State two fundamental properties of optical transmission (in a medium) that would degrade performance? [2]

Scattering of the light [1]
Absorption in a material [1]

The function of this BMI is to record extracellular action potentials from a microelectrode array. Assuming that each channel will record spikes from at most three different neurons, and that these spikes will have distinct features (example spikes shown in Figure 5.1), it is required to classify the spikes (i.e. being able to identify which spike shape is being recorded).

d) Sketch a typical block diagram for classifying these spikes (after amplification and filtering). [3]

Spike detection [1]
Spike alignment or Feature Extraction [1]
Clustering [1]

e) To reduce the communication bandwidth (i.e. data rate), it is proposed to extract specific features from each spike recorded and transmit only these, instead of the entire raw signal. Identify two different features that could be used to distinguish between different spike shapes (for spike sorting)? [2]

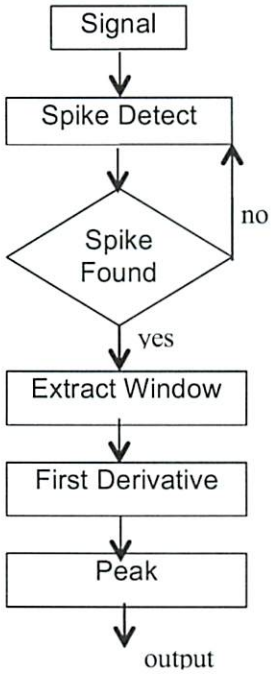
[Test knowledge and understanding]
Several possible variations accepted:
1. *First Derivative or Slope features - minima or maxima [1]*
2. *Second Derivative features - minima or maxima [1]*
3. *Minimum signal peak position [1]*
4. *Zero-crossing features [1]*
5. *Area-based information [1]*
6. *Time-frequency or energy approach [1]*

Emphasis on features not standard methods such as Principal Component Analysis (PCA), Support Vector Machines (SVM), neural networks.

f) Sketch a flow chart for detecting and extracting one of the features identified previously in your answer to part (e). Given that the positive spike peaks (shown in Figure 5.1) vary from 0.75±0.25mV, and negative peaks vary from -0.75±0.25mV, estimate the range and resolution required to represent the feature selected. State any assumptions made. [5]

[Test knowledge and understanding beyond the notes]
Typical Flow Chart must include 3 of the following:

1. *Spike Detection (will always be necessary) and Windowing (if necessary for the feature) [1]*
2. *Their feature extraction methodology in a clear concise manner, first derivative peak example shown below [2]*

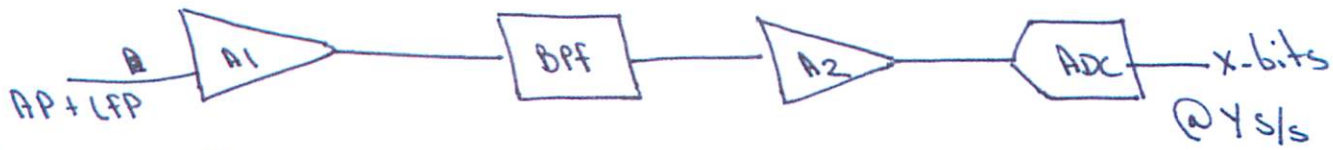


Once drawn a clear calculation flow needed for their feature of interest. This example: Assuming peak of signal first derivative is given by the second slope and slope approximately 0.1-0.5ms in duration [1]

Therefore (from plots) derivative of this slope will vary from 1mV/0.5ms to 2mV/0.1ms which gives 2 to 20, so 5 bits needed. [1]

(6) Neuroprosthetics question

(a)



(5μV rms noise)

if EAP range is 500μV max (ptp) to map onto 3.3V range (data converter) → need a total gain of 6600 = 76.4 dB.

If we require to limit i/p range to filter to say 50mV ptp.

→ set A1 = 100 = 40dB

A2 = 66 = 36.4dB [2]

---

if noise at input = 5μV rms

at output (i/p to ADC) = 5μV × 6600 = 33mV

∴ Set LSB to be ½ noise at o/p = $\frac{33}{2}$ = 16.5mV.

∴ Dynamic range = $\frac{3300}{16.5}$ = 200 ⇒ 8-bit resolution [2]

Given the BW of EAP is 300Hz - 3kHz set sampling rate to

5× f_{max} = 5 × 3kHz = 15kHz [2]

∴ A_1 = 100, A_2 = 66, X = 8-bit, Y = 15k Sample/s.

(b) Bits required per second (per channel)

= 8 × 15000 = 120 000 bps = 120k bps.

∴ Given telemetry of 10 Mbps ⇒ channels = $\frac{10M}{120k}$

≈ 83 channels

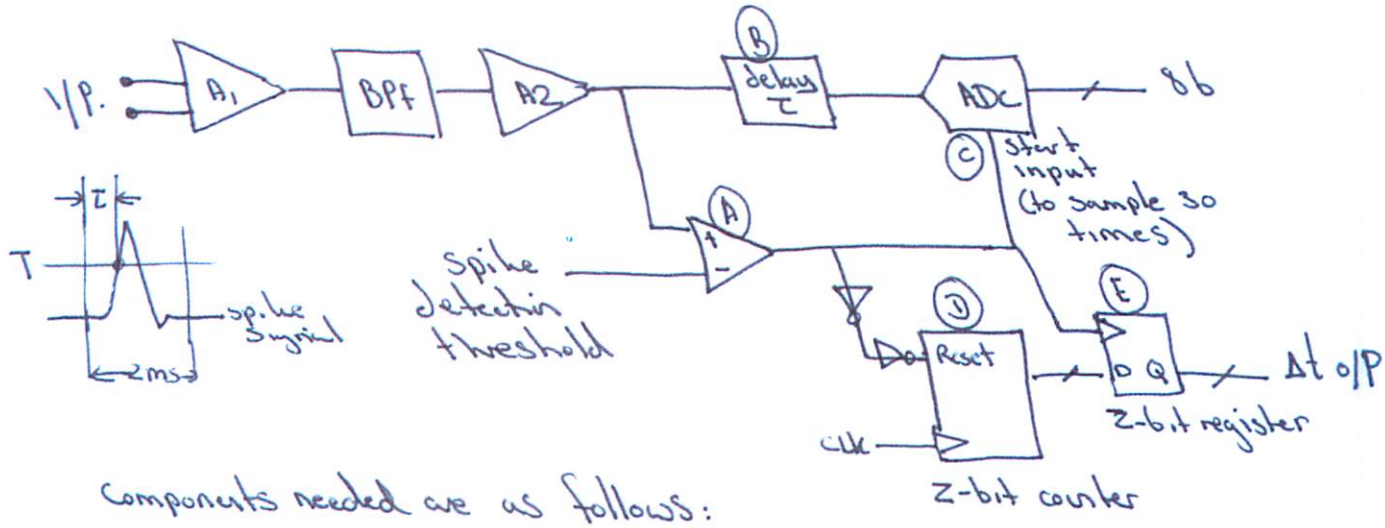
[2]

(c) Can modify the circuit to do spike detection such as to window the signal and communicate only the spike shapes.

~~Given~~
Assuming the "length" of each spike is 2ms and on average, each neuron will spike 25 times/s and that each electrode will on average record from 2.5 neurons sets datarate (per channel) to:

$$\left(\frac{2\text{ms}}{1/15\text{kS/s}}\right) \times 25 \times 2.5 \times 8 = 15\text{kbps}.$$

∴ A 10Mbps communication link would now support $\frac{10\text{M}}{15\text{k}}$
= 667 channels



Components needed are as follows:

(A) Comparator for comparing recording to a fixed threshold (for detection)

(B) Analogue delay such that the signal "before" the spike threshold is still sampled (see spike above)

(C) A start "trigger" to ADC to ~~sample~~ take 30 successive samples (can be achieved with simple counter).

(D) ~~An~~ Counter to track time interval between spikes (it is reset each time a spike is detected).

(E) Register to store intervals before reset.

(d) Low power consumption is <u>essential</u> because:

- energy capacity in batteries is limited and so are total charge/discharge cycles → maximum useable lifetime.
- energy consumed is ultimately dissipated as heat ∴ low powers for safety → to avoid tissue damage.
- If channel circuit is made to consume minimum power possible → given a power budget can have more channels. [3]

(e) This device would be classified as a Class III device indicating it is in the highest risk category. This is because any implantable device is invasive by nature. [1]

US regulatory body is the food and Drug Administration (FDA) [1]