# UNIVERSITY OF SWAZILAND
# SUPPLEMENTARY EXAMINATION, JULY 2015

## FACULTY OF SCIENCE AND ENGINEERING

## DEPARTMENT OF ELECTRICAL AND ELECTRONIC ENGINEERING

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|---|---|
| **TITLE OF PAPER:** | **INSTRUMENTATION SYSTEMS** |
| **COURSE NUMBER:** | **EE521** |
| **TIME ALLOWED:** | **THREE HOURS** |

**INSTRUCTIONS:**

1. There are five questions in this paper. **Answer any FOUR questions.**
2. Each question carries 25 marks.
3. Marks for different sections are shown on the right hand margin.
4. Show the steps clearly in all your calculations including any assumptions made. This is because marks may be awarded for method and understanding, even in the event of incorrect answers.
5. A table of standard values of 1% tolerance resistors and a table of common capacitor values are attached at the end of the question paper for your use in designs.

THIS PAPER IS NOT TO BE OPENED UNTIL PERMISSION HAS BEEN GIVEN BY THE INVIGILATOR

**THIS PAPER HAS SEVEN (7) PAGES INCLUDING THIS PAGE**

**QUESTION 1** ***(25 marks)***

**(a)** Distinguish between the following terms as used in the characterization of instruments and sensors;

(i) Accuracy and precision *(2 marks)*

(ii) Sensitivity and Resolution *(2 marks)*

(iii) Span and range *(2 marks)*

(iv) Zero drift and sensitivity drift *(2 marks)*

**(b)** A load cell to be used to measure weight in the range 0 to 12 kg was tested and gave the following output voltages:

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| Weight, kg | 0.0 | 2.0 | 4.0 | 6.0 | 8.0 | 10.0 | 12.0 |
| Output, mV | 6.24 | 7.30 | 8.48 | 9.72 | 10.72 | 12.04 | 13.30 |

**(i)** Calculate the sensitivity and zero offset of the load cell. A calculator in linear regression mode may be used and units must be stated. *(5 marks)*

**(ii)** The output of this load cell is to be fed into an analogue-to-digital converter (ADC) chip which has an input analogue signal range of 0 V to 5 V. Design a suitable circuit to interface the load cell to the ADC. *(12 marks)*

## QUESTION 2 *(25 marks)*

Consider the three-opamp configuration of an instrumentation amplifier (IA) shown in Fig. Q2. The amplifier is used for amplifying the output of a differential signal fed in at signal inputs $v_1$ and $v_2$. The opamps A1, A2 and A3 may be assumed to be ideal and the CMRR should be maximized so that $v_o \simeq k(v_2 - v_1) = kv_{id}$.

**(a)** Derive relevant expressions giving the relationship between the output voltage and the differential input voltage. *(9 marks)*

**(b)** Derive the relationship between the resistors so that maximum CMRR is obtained. *(7 marks)*

**(c)** You are required to design the IA with an overall differential gain of 1000. Practical limitations indicate that the values of the resistors used should be 10 kΩ or larger. Specify the values of all the resistors you would use in this circuit. *(7 marks)*

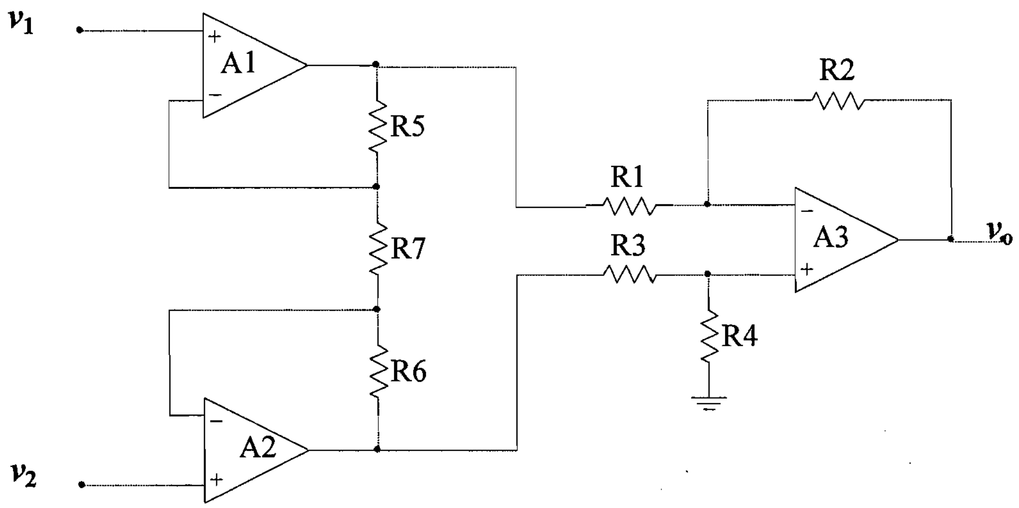


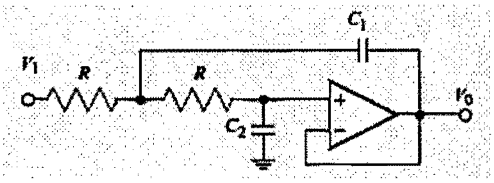

**Fig.Q2**

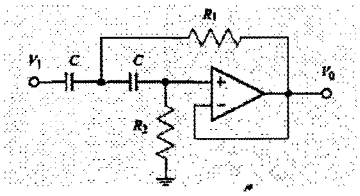
**(d)** A differential voltage of up to 11 mV peak amplitude is applied at the inputs of the IA. If the amplifiers are capable of producing an output voltage of amplitude to within 1 V of the power supply voltage without saturation, what should be the minimum supply voltage for the amplifiers to operate without clipping the signal. *(2 marks)*

## QUESTION 3 *(25 marks)*

**(a)** Use the data given below to design a Butterworth **low-pass** four-pole active filter with cut off frequency 15 kHz. *(10 marks)*

The following data applies to a unity gain Sallen-Key Lowpass and Highpass Configuration active filters. Notice resistors are equal in lowpass and capacitors are equal in Highpass.




| | Butterworth | | Transitional | | Bessel | | Chebyshev (0.5 dB) | |
|---|---|---|---|---|---|---|---|---|
| Poles | $k_1$ | $k_2$ | $k_1$ | $k_2$ | $k_1$ | $k_2$ | $k_1$ | $k_2$ |
| 2 | 1.414 | 0.707 | 1.287 | 0.777 | 0.907 | 0.680 | 1.949 | 0.653 |
| 4 | 1.082 | 0.924 | 1.090 | 0.960 | 0.735 | 0.675 | 2.582 | 1.298 |
| | 2.613 | 0.383 | 2.206 | 0.472 | 1.012 | 0.390 | 6.233 | 0.180 |
| 6 | 1.035 | 0.966 | 1.060 | 1.001 | 0.635 | 0.610 | 3.592 | 1.921 |
| | 1.414 | 0.707 | 1.338 | 0.761 | 0.723 | 0.484 | 4.907 | 0.374 |
| | 3.863 | 0.259 | 2.721 | 0.340 | 1.073 | 0.256 | 13.40 | 0.079 |
| 8 | 1.019 | 0.981 | 1.051 | 1.017 | 0.567 | 0.554 | 4.665 | 2.547 |
| | 1.202 | 0.832 | 1.191 | 0.876 | 0.609 | 0.486 | 5.502 | 0.530 |
| | 1.800 | 0.556 | 1.613 | 0.615 | 0.726 | 0.359 | 8.237 | 0.171 |
| | 5.125 | 0.195 | 3.373 | 0.268 | 1.116 | 0.186 | 23.45 | 0.044 |

***Source*: Brian K. Jones, *Electronics for Experimentation and Research*, Prentice Hall, Englewood Cliffs, NJ, 1986. By permission of Prentice-Hall International (UK) Ltd, London.**

Where for **Lowpass:** $RC_1\omega_c = k_1$ and $RC_2\omega_c = k_2$. Higher-order filters use cascaded stages.

For **Highpass:** $R_1C\omega_c = 1/k_1$ and $R_2C\omega_c = 1/k_2$. Higher-order filters use cascaded stages.

**(b)** A measurement signal, with frequency 10 Hz, is accompanied by an interference signal with the same amplitude but of frequency 100 Hz. Both signals are passed through a Butterworth filter. It is required that the measured signal emerges with 0.9 of its original amplitude while interference signal emerges with 1/200th of its original amplitude. Find the minimum order and cut off frequency of the Butterworth filter.

Response of *n*th order Butterworth lowpass filter is given by $\left|\frac{v_o}{v_{in}}\right| = \frac{1}{\sqrt{1+\left(\frac{f}{fc}\right)^{2n}}}$.

*(15 marks)*

**QUESTION 4** ***(25 marks)***

**(a)** Consider the half bridge circuit shown in Fig. Q2a

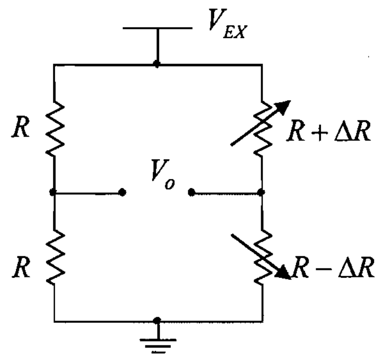



Fig. Q2a

(i) Derive an expression for the output voltage $V_o$ of the circuit. *(6 marks)*

(ii) Describe using an appropriate sketch how this circuit may be used to remove the temperature error in load measurements based on bending of beams. *(5 marks)*

(b) The Steinhart- Hart equation for a thermistor is given by:

$$\frac{1}{T} = A + B\ln R + C(\ln R)^3,$$ where $T =$ Absolute temperature (K),

$R =$ resistance of the thermistor and $A$, $B$ and $C$ are constants

A typical thermistor has the following coefficients for the Steinhart- Hart equation:

A = 1.1252 × 10–3/K, B = 2.3478 × 10–4/K, C = 8.5262 × 10–8/K

Calculate the temperature in °C when the resistance of the thermistor is 3000 Ω.

Note that 0 K = -273.15 °C. *(6 marks)*

(c) A CdS cell (LDR) has a dark resistance of 120 kΩ and its resistance in a light beam of 18 $mW/cm^2$ is 30 kΩ. The cell has a first-order response time constant of 60 ms. We want to trigger a comparator with a threshold voltage of 1.5 V within 30 ms of the interruption of a 18 $mW/cm^2$ beam shone on the cell. Design a circuit to trigger the comparator.

*(8 marks)*

**QUESTION 5** ***(25 marks)***

**(a)** A signal conditioning circuit with four opamps is shown in Fig.Q5a. The nodes 0 are at zero ground potential.

Calculate the voltages expected at all the nodes which have been marked 1 to 10.

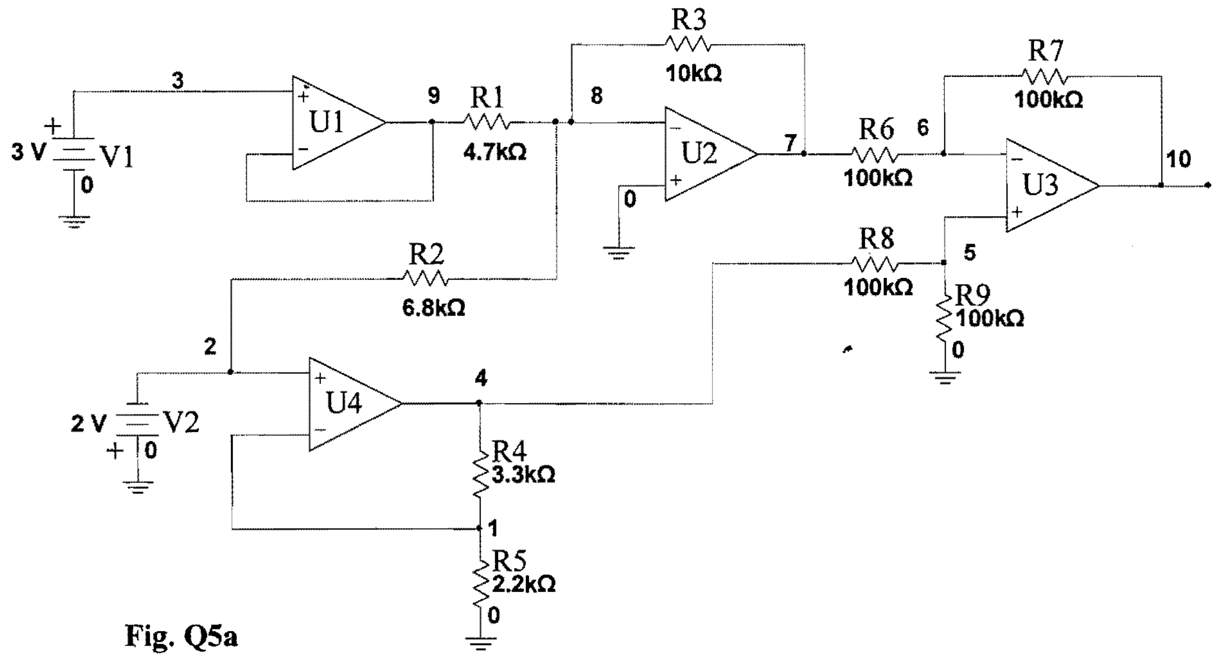



**Fig. Q5a**

*(10 marks)*

**(b)** A loop current transmitter is based on the circuit in Fig. Q5b. The circuit is required to give an output current $I_o$ of 2 mA with input voltage $v_{in}$ of 0 V, and 20 mA with an input voltage of 2 V. The opamp used needs power supplies of ±15 V and its saturation occurs at output voltages of ±13 V. Complete the design of the circuit by specifying values of $V_{ref}$, $R$, $R_S$ and maximum value of load resistance $R_L$ . *(15 marks)*

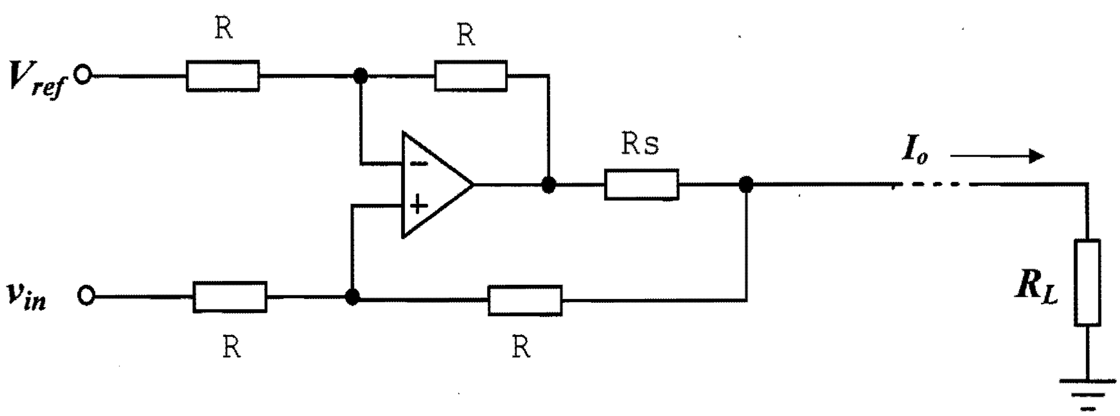



**Fig. Q5b**

# VALUES OF STANDARD 1% TOLERANCE RESISTORS

| | | | | | | |
|---|---|---|---|---|---|---|
| 100 | 140 | 196 | 274 | 383 | 536 | 750 |
| 102 | 143 | 200 | 280 | 392 | 549 | 768 |
| 105 | 147 | 205 | 287 | 402 | 562 | 787 |
| 107 | 150 | 210 | 294 | 412 | 576 | 806 |
| 110 | 154 | 215 | 301 | 422 | 590 | 825 |
| 113 | 158 | 221 | 309 | 432 | 604 | 845 |
| 115 | 162 | 226 | 316 | 442 | 619 | 866 |
| 118 | 165 | 232 | 324 | 453 | 634 | 887 |
| 121 | 169 | 237 | 332 | 464 | 649 | 909 |
| 124 | 174 | 243 | 340 | 475 | 665 | 931 |
| 127 | 178 | 249 | 348 | 487 | 681 | 953 |
| 130 | 182 | 255 | 357 | 499 | 698 | 976 |
| 133 | 187 | 261 | 365 | 511 | 715 | |
| 137 | 191 | 267 | 374 | 523 | 732 | |

d

# COMMON STANDARD VALUES OF CAPACITORS

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 10 | 15 | 22 | 33 | 47 | 68 | pF | Non-polarized |
| 100 | 150 | 220 | 330 | 470 | 680 | pF | Non-polarized |
| 1 | 1.5 | 2.2 | 3.3 | 4.7 | 6.8 | nF | Non-polarized |
| 10 | 15 | 22 | 33 | 47 | 68 | nF | Non-polarized |
| 100 | 150 | 220 | 330 | 470 | 680 | nF | Non-polarized |
| 1 | 1.5 | 2.2 | 3.3 | 4.7 | 6.8 | µF | Non polarized /Polarized |
| 10 | 15 | 22 | 33 | 47 | 68 | µF | (Polarized) |
| 100 | 150 | 220 | 330 | 470 | 680 | µF | (Polarized) |
| 1000 | 1500 | 2200 | 3300 | 4700 | 6800 | µF | (Polarized) |

Butterworth HP filter $\left|\frac{v_o}{v_{in}}\right| = \frac{f/\mathrm{f}_c}{\sqrt{1+(f/\mathrm{f}_c)^{2n}}}$, Butterworth LP filter $\left|\frac{v_o}{v_{in}}\right| = \frac{1}{\sqrt{1+(f/\mathrm{f}_c)^{2n}}}$

First order response $a_1\frac{ds_o}{dt} + a_o s_o = b_o s_i$ or $\tau\frac{ds_o}{dt} + s_o = Ks_i$ and for step response $s_o / s_i = K(1-e^{-t/\tau})$