UNIVERSITY OF TORONTO

FACULTY OF APPLIED SCIENCE AND ENGINEERING

FINAL EXAMINATION - TUESDAY, DECEMBER 11, 2001

IV-AEMECBASC, AEMECBASCT, AEESCBASCA, AEESCBASCB(E), AEESCBASCM

ECE 471HF - INSTRUMENTATION DESIGN

Exam Type: D

Examiner: Hana Hnik

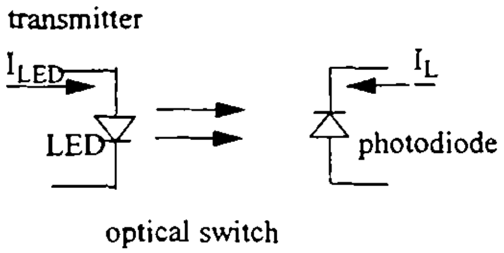
Four solved questions constitute a complete paper. Relative weight of each question is indicated at each question.

Wherever applicable, derive first expressions in terms of system parameters, then substitute numerical values.
Clearly state design criteria and assumptions made.

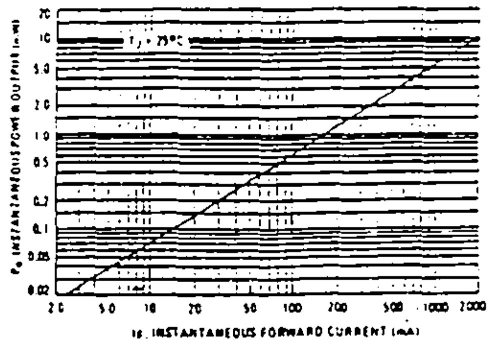
This is an open-book examination. The Instrumentation Notes book and a double-sided hand-written aid sheet is permitted.

Question #1) 20%
You are to design an on-off light detector that uses an infrared optical switch as a fundamental design compnent.

A block diagram of the infrared-light optical switch is as shown. A GaAs (gallium arsenide) light emitting diode (LED) type MLED 930 is used as a transmitter and a GaAs photodiode as a receiver.



Instantaneous Light Output versus Forward Current For The MLED 930



Part i) Determine a value of the DC bias current I_{LED} through the transmitting diode that causes the optical current, I_L through the receiving photodiode equal 60 μ A, under uninterupted illumination from the LED. Show your computations, state assumptions made.

Specifications:

A value of the GaAs energy band gap, E_G, equals to 1.42 eV at 300°K.

The maximum quantum efficiency occurs at wavelength $\lambda < \lambda_{critical}$ (at approximately $\lambda = 0.9\lambda_{critical}$). Effective illuminated area of the photodiode is $4mm^2$.

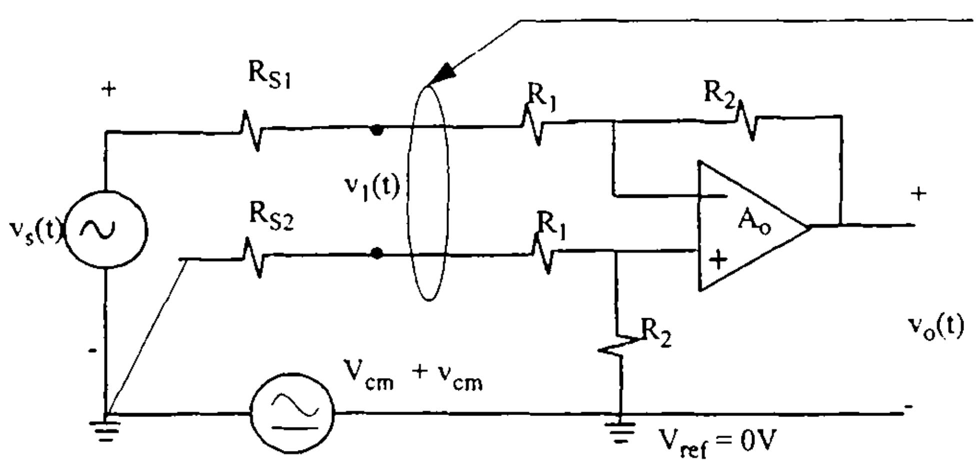
The light-power output versus forward DC bias current for the LED used is as shown on a graph attached. The light-power radiation from the LED diode is uniform and assumed spherical. Distance between the transmitter and the receiver is 3mm.

Part ii) Use a single DC power supply of +6V and design a light detector circuit (based on values obtained in Part i)).
Suggestion: Place a resistor R_{LED} in series with the transmitting LED diode and another resistor R_L in series with the receiving photodiode.
Use a computed value of current I_{LED} and find a value of resistor R_{LED} so that the required DC bias conditions for the LED are satisfied. Assume V_{LED} across the forward biased diode equal to 1.7V.
Then select a value of resistor R_L so that a voltage across the resistor equals 5V under uninterrupted illumination and 0V (or close to 0V) under blocked (no) illumination.

Part iii) Sketch a detailed circuit diagram of the light detector. Show polarities of all voltages, directions of all currents and a proper orientation of the diodes.
Explain briefly how the circuit works and suggest its applications.

Question #2) 20%

Signal from a bridge transducer, with an equivalent electrical circuit as shown, is amplified using one op-amp instrumentation amplifier.



Specified:

Transducer output resistance, $R_{S1} = 1k\Omega$, $R_{S2} = R_{S1} + \Delta R_S$.

Summing resistors $R_1 = 20k\Omega$, feedback resistors $R_2 = 20k\Omega$, specified tolerances of the resistors are 0.05%.

The CMR of the op-amp is 120dB at DC, it rolls of at -20dB/dec from frequency f_o= 6 Hz.

Common mode voltages, V_{cmDC} = 2V DC, $v_{cm} = 1\cos 2\pi 60t$.

Part i) First assume $R_{S1} = R_{S2} = 0\Omega$ and provide an expression for computation of the worst-case $CMRR_{\Delta R}$ caused by the summing and feedback resistor mismatch of the one op-amp instrumentation amplifier itself. Express the $CMRR_{\Delta R}$ in terms of $\frac{\Delta R}{R}$, which constitutes resistor tolerances.

Part ii) Compute a numerical value of the $CMRR_{\Delta R}$ for $R_S = 0\Omega$.

Part iii) Find a largest mismatch allowed (in Ω) between the source resistors R_{S1} and R_{S2}, a restriction is that the common mode error caused by the R_S resistor mismatch is not to exceed a common mode error caused by the tolerances (mismatch) of resistors R_1 and R_2.

Part iv) After determining the largest R_S mismatch allowed, compute the overall absolute error of the system (in V_{RMS}) caused by the common mode voltages, V_{cm} and v_{cm}. Relate the error to the input (RTI) of the amplifier.

Part v) Is the above system suitable to amplify signals from strain-gauge based bridge sensors? Explain briefly.

Question #3) 30%

You are to provide key specifications needed for selection of a data acquisition system that is to be used to condition and digitize signals from four thermocouple-based sensors that measure exhaust temperature of two aircraft engines. The data acquisition system is to be located in the cockpit, 20m away from the sensors.

The thermocouple sensors are to be balanced for 0V output at 0°C. The temperature coefficient of the thermocouples is $+40\mu$ V/°C. Expected temperature range to be measured is 20°C to 1200°C.

There is a considerable electromagnetic radiation at frequencies 400Hz and at 1MHz, caused by other circuits in the aircraft.

A block diagram of a proposed data acquisition system is as shown in Fig 1. Only one channel is shown. Each channel is to have its own amplifier and filter.

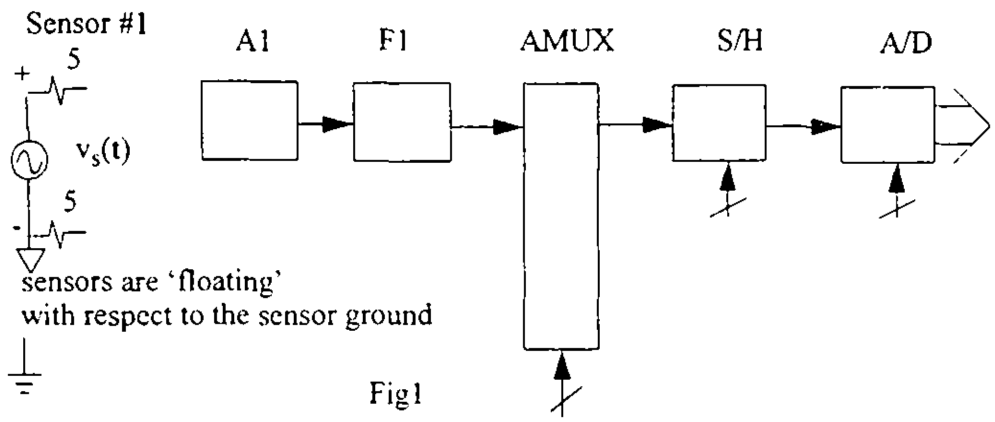


Fig1

Amplifiers used are three op-amp instrumenation amplifiers. Value of the amplifiers input resistance should be higher than $1M\Omega$.

The A/D converter is a successive approximation A/D converter with the full-range analog input voltage equal to 0 to 5V.

Part i) Determine the full-range output voltage at the output of the thermocouple sensors. Are the sensor output signals bipolar or unipolar? Signal passbands are assumed rectangular of frequencies 0 to 2Hz and of magnitudes equal to V_{FS}.

Part ii) Based on the information given determine parameters associated with individual design components of the data acquisition system:

Question #3 cont.d

For the **Amplifiers**:

a) Determine the voltage gain, A_V, of the amplifiers so that the sensitivity of the system, in terms of the amplifier output voltage per degre Celsius, equals 4 mV/°C.
Specify a value of the full-scale voltage at the output of the amplifiers.

For the **Filters:**

a) Determine types of the filters (LPF, HPF, Butterwort, Chebyshev...). Justify your choice and explain a purpose of the filters.

b) Specify the gain, the cut-off frequency, and the order of the filters. State your criteria, show your computations.

Choice of the **Sampling Frequency:**

a) Determine a minimum sampling frequency per channel. The accuracy requirement states that a value of the average absolute sampling error carried by each sampled signal is not to exceed voltage corresponding to 10°C. (A relatively large sampling error is to be minimized by additional filtering when engine exhaust temperatures are to be monitored).

b) What is the minimum throughput rate of the system? Explain your aswer.

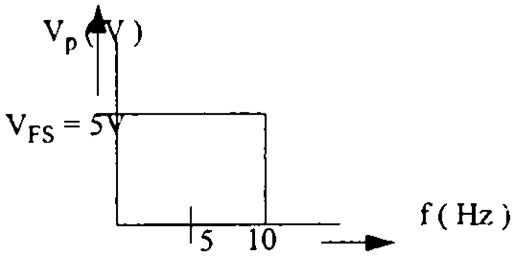
Choice of an **A/D converter:**
a) How many bits will be required for the A/D converters? The RMS value of the quantiza tion error carried by the signals is to be smaller than a voltage corresponding to 2°C.

Grounding and shielding arrangements of sensor-amplifier interconnecting cables.
Sketch a circuit diagram of a sensor-interconnecting cable-amplifier system (one channel only) and indicate grounding and shielding arrangements of the sensor, of the interconnect ing cable, and of the amplifier. A shielded twisted pair of wires is to be used.
Note that the sensors are floating with respect to the ground and that the amplifiers have to have a DC path to the ground for DC bias currents to flow.

Accuracy
a) Compute a value of an overall error carried by the digitized signals. Express the error in terms of °C and in % FS.

Question #4) 30%

Ten bipolar signals, each with the spectral representation as shown, have been processed digitally. Prior to digital processing each signal has been sampled at the sampling frequency $f_s = 1kHz$ and digitized using an 8-bit successive approximation analog-to-digital converter of $V_{FR} = 0$ to 10V,



After digital processing the signals are to be demultiplexed digitally and then reconstructed to their analog equivalents. Each channel has its own reconstruction S/H device followed by a smoothing second-order low-pass filter.
The sampling frequency per channel is to be maintained.

Part i) Sketch a block diagram of the reconstruction system.

Part ii) Sketch the time-domain representation of one of the reconstructed signals as it appears at the output of the reconstruction S/H device. Label the time axis.

Part iii) Sketch the frequency-domain representation of one of the reconstructed signals as it appears at the output of the reconstruction S/H device. Label the frequency axis.
Also show a sampling noise and a quantization noise. Indicate the associated passbands.
Indicate on the same graph how a low-pass filtering minimizes both the sampling noise as well as the quantization noise. Explain briefly.

Part iv) Write an expression (in general terms) for the absolute quantization error (in V_{RMS}) carried by each signal at the output of the S/H device.
Compute a value of the quantization noise (in V_{RMS}).

Part v) Use the frequency-domain representation of the quantization noise and derive (write) an expression for the maximum signal-to-noise ratio $SNR_{maxS/H}$ (due to the quantization noise) associated with the signals at the output of the reconstruction S/H devices. Express the $SNR_{maxS/H}$ in terms the oversampling rate, OSR.
Compute a numerical value of the $SNR_{maxS/H}$. Express the $SNR_{maxS/H}$ in decibels.

Part vi) Use the frequency-domain representation of the quantization noise and derive (write) an expression for the SNR_{maxLP} (caused by the quantization error) associated with each signal at the output of a reconstruction filters. For computational purposes assume ideal reconstruction LP filters with the frequency response that matches the signal passbands, $0\text{-}f_0$.
Express the SNR_{maxLP} in terms of the oversampling rate, OSR.
Compute a numerical value of the SNR_{maxLP}. Express the value of SNR_{maxLP} in decibels.