BME/ECE 386 FINAL (W19) NAME: Solutions

5 problems for 100 pts

Problem #1: General Knowledge (25 pts)

(a) Electronics (4 pts): Choose true or false for each of the following statements. **If you choose false, then provide the correct statement.**

(i) If an instrumentation amplifier has A_d = 500 and CMRR = 90 dB, then its common-mode gain is A_{CM} = 0.16.

(ii) Aortic devibration is the major cause of death due to electric shock.

(iii) A microshock can be caused by small inductively-coupled currents flowing into the body via a catheter.

(i) False $90 = 20\log_{10}\left(\frac{500}{A_{CM}}\right) \rightarrow 10^{90/20} = \frac{500}{A_{CM}}$

$A_{CM} = .0158$

(ii) False V-fib (ventricular fibrillation)

(iii) False capacitively coupled

(b) Temperature (4 pts): Choose true or false for each of the following statements. **If you choose false, then provide the correct statement.**

(i) Temporal artery thermometry measures the amount of ultraviolet rays reflected from the temporal artery.

(ii) The Seacrest effect produces a small current difference to appear between the hot and cold end of a metal wire.

(iii) The Steinway-Bort equation determines the relationship between thermocouple resistance and temperature.

(i) False infrared rays emitted

(ii) False Seebeck, voltage difference

(iii) False Steinhart-Hart eqn, thermistor resistance

(c) Electrophysiology (4 pts): Choose true or false for each of the following statements. **If you choose false, then provide the correct statement.**

(i) In EMG, the basic neuromuscular unit is called the neural control unit (NCU) and consists of a sensory neuron and bundle of ligament fibers.

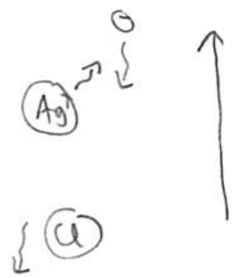
(ii) The electrical signal that stimulates the ventricles is delayed by the Schwann-Purkinje node, thereby ensuring the upper and lower ventricles depolarize after the front and back alveoli.

(iii) For ECG electrodes, the oxidation of adamantium ions and association of dilithium sulfide are responsible for current flowing out of the body.

(i) False SMU (single motor unit) = Motor neuron + muscle fiber bundle

(ii) False Atrio Ventricular (AV) node
L+R ventricles
L+R atria

(iii) False Reduction of Ag
Dissociation of AgCl



(d) Circulation (4 pts): Choose true or false for each of the following statements. **If you choose false, then provide the correct statement.**

(i) During diastole, the midas and biannual values are closed.

(ii) A systolic pressure of 2 psi is indicative of hypertension.

(iii) Given a cardiac output of 5.8 L/min and a stroke volume of 80 mL, the corresponding heart rate is 1.5 beats per second.

(i) False mitral + tricuspid open or aortic + pulmonary closed

(ii) False $2\,psi \times \frac{760\,mmHg}{14.7\,psi} = 103.4\,mmHg$ ← Low!

(iii) False $SV \times HR = \frac{5.8L}{min} \Rightarrow HR = \frac{5.8L}{min} \times \frac{1}{.080L} \times \frac{1\,min}{60s}$
$= 1.2$ beats/sec

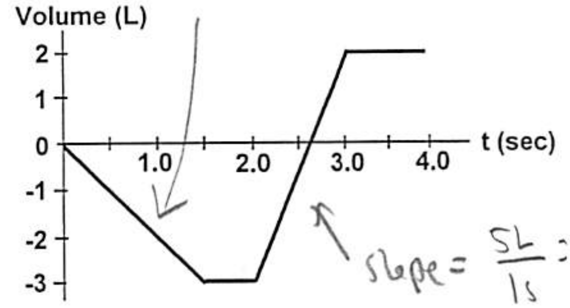
(e) Respiration (4 pts):

slope $= \frac{-3L}{1.5s} = -2\,L/s$

(i) (True or False) Vital capacity is the difference between total lung capacity and expiratory reserve volume. **If you choose false, then provide the correct statement.**

(ii) Given the volume plot on the right, sketch the corresponding flow plot. Label the peak expiratory flow!

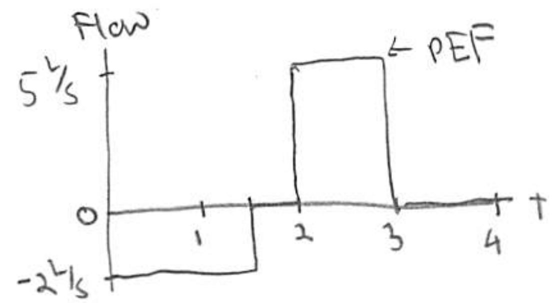
(iii) A helium dilution method uses an 8L volume spirometer with an initial He concentration of 4%. If the final He concentration is 3%, what is the patient's FRC? Express your answer in liters.

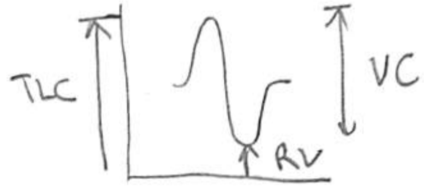


slope $= \frac{5L}{1s} = 5\,L/s$

(i) False $VC = TLC - RV$

(ii)





(iii)

$C_S V_S = C_{LS}(V_S + V_L)$

$\frac{C_S V_S - C_{LS} V_S}{C_{LS}} = V_L = \frac{4-3}{3\%} \cdot 8L$

2.67L

(f) Medical imaging (5 pts): Choose true or false for each of the following statements. **If you choose false, then provide the correct statement.**

(i) Indium is a common x-ray contrast agent for angiography.

(ii) In MRI, the primary magnet is a coil of copper wire cooled by dry ice.

(iii) Cubic zootopia titanate is a common pyrotechnic material used for medical ultrasound transducers .

(iv) X-ray detection involves a two-step process involving a fluorescent layer on top of a photodetector array.

(i) False Iodine

(ii) False Niobium · Titanium , liquid He

(iii) False PZT (Lead zirconate Titanate) piezoelectric

(iv) False Phosphor layer

Problem #2: Medical Device Regulation (15 pts)

(a) FDA (5 pts): Choose true or false for each of the following statements. **If you choose false, then provide the correct statement.**

(i) The Center for Biologics Evaluation and Research (CBER) oversees devices related to urine testing.

(ii) A device recall is issued by the FDA and does not have to be in consultation with the manufacturer.

(iii) The Medical Device Amendments of 1985 established the first recall requirements for devices.

(iv) The Center for Gizmos and Perpetual Health (CGPH) is the FDA branch that oversees device regulation.

(i) False — Blood

(ii) False — Issued by manufactures in consultation w/ FDA

(iii) False — MDA of 1976, premarket requirements

(iv) False — CDRH (Center for Devices and Radiological Health)

(b) Clearance/Approval (5 pts): Choose true or false for each of the following statements. **If you choose false, then provide the correct statement.**

(i) A device receives FDA clearance if it is shown to be substantially equivalent to a device before 1985.

(ii) A premarket notification, also called a 403(b), applies mostly to low risk devices.

(iii) The three device classifications (Class A, B, and C) are based on anticipated cost of the device.

(iv) In order to obtain FDA approval, a manufacturer must submit a postmarket application (PMA).

(i) False — 1976

(ii) False — 510(k)

(iii) False — Class 1, 2, 3, level of risk

(iv) False — Premarket application (PMA)

(c) Postmarket (5 pts): Choose true or false for each of the following statements. **If you choose false, then provide the correct statement.**

(i) The FDA provides manufacturers with a detailed list of manufacturing procedures that is customized to each device that receives clearance or approval.

(ii) Proper labeling includes pamphlets, posters, and brochures about the marketed device.

(iii) The production of any FDA cleared or approved device must follow the General Machining Protocol (GMP).

(iv) Medical Device Reporting (MDR) regulations require user facilities to report device problems to the FDA and manufacturer within 14 work days of the event.

(i) False broad guidelines

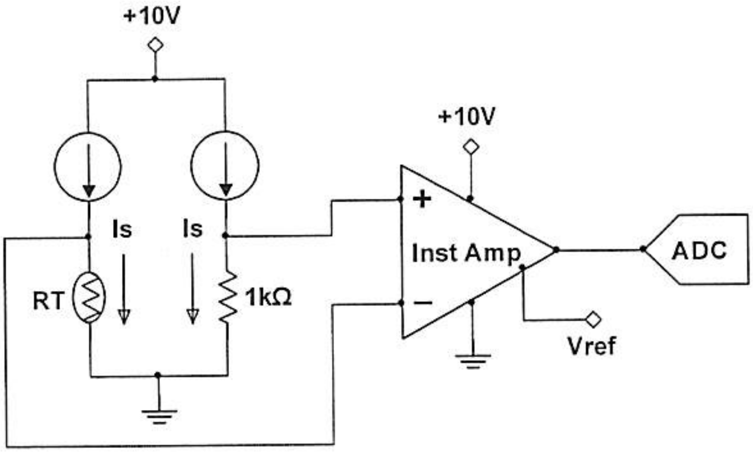
(ii) True

(iii) False GMP = Good Manufacturing Practice

(iv) False 10 work days

Problem #3: Temperature (20 pts)

A biochemistry experiment requires a temperature measurement system operating from T = 20°C to 50°C with a sensitivity of 0.02°C at T = 50°C. Furthermore, self-heating must be small enough that $\Delta T_{SELF} \leq 0.5 \Delta T_{MIN}$ at T = 50°C.



- You decide to use a thermistor R_T driven by a constant current source I_S = 150 µA.

  NOTE: This means the current through RT is always equal to I_S.

- An identical current source drives a 1 kohm resistor.
- Two amplifiers are available: A_d = 10 (V_N = 300 µV) and A_d = 50 (V_N = 1.5 mV).
  - Both amplifiers have Vref = 3V.
  - Assume the maximum amplifier outputs are 1V less than the power supplies.
- The ADC operates from 0 to 10V with 14 bits.
- The 1 kohm thermistor (see table) has a dissipation coefficient of 2 mW/°C.

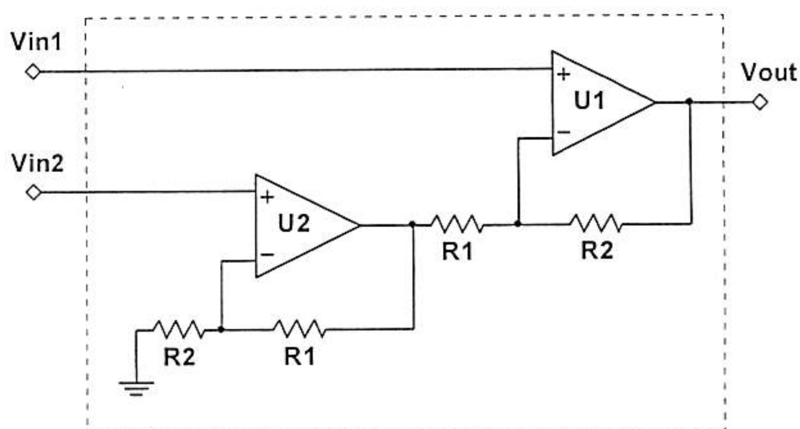
Temp	R_T (ohm)	Tempco (%/°C)
20°C	1217	-3.99
25°C	1000	-3.87
50°C	407	-3.32

a) Are all the design specs satisfied using one, both, or none of the amplifiers? Show all work! You must be VERY CLEAR about why an amplifier works or does not work.

b) Suppose there is a worldwide shortage of instrumentation amplifier chips. ☹ Fortunately, two op-amps can form an instrumentation amplifier with very high input impedance and good CMRR. **Use the Golden Rules to show that:**

$$V_{OUT} = \left(1 + \frac{R_2}{R_1}\right)(V_{in1} - V_{in2})$$

Show all work!



(a) $V_M = 3 + A_d \Delta V = 3 + A_d I_s (1K - R_T)$ $1 < V_M < 9V$

$T = 50°C$: $1K - R_T = 1 - .407 = .593K$

$A_d = 10$: $V_M = 3 + 10(.15mA)(.593K) = 3.89V$ ✓   (+3)

50: $V_M = 3 + 50(.15mA)(.593K) = 7.45V$ ✓

$T = 20°C: \quad 1K - R_T = 1 - 1.217 = -.217K$

(extra sheet for work)

$A_d = 10: \quad V_M = 3 + 10(.15)(-.217) = 2.67V$ ✓

$50: \quad V_M = 3 + 50(.15)(-.217) = 1.37V$ ✓

(+3)

$$\Delta T_{MIN} = \frac{\Delta V_{MIN}}{\frac{\partial V_M}{\partial T}} \qquad \Delta V_{ADC} = \frac{10 - 0V}{2^{14} - 1} = .61mV$$

$$\frac{\partial V_M}{\partial T} = \frac{\partial V_M}{\partial R_T} \alpha R_T = -A_d I_s \alpha R_T$$

$A_d = 10: \quad V_N = .3mV \rightarrow \Delta V_{MIN} = .61mV$

$$\frac{\partial V_M}{\partial T} = -10\,(.15mA)(-.0332\ 1/°C)(.407K) = .02\ V/°C$$

$$\Delta T_{MIN} = \frac{.61 \times 10^{-3}\ V}{.02\ V/°C} = .03°C$$ ✗ Too big.

(+3)

$A_d = 50: \quad V_N = 1.5mV \rightarrow \Delta V_{MIN} = 1.5\ mV$

$$\frac{\partial V_M}{\partial T} = -50\,(.15)(-.0332)(.407K) = 0.1\ V/°C$$

$$\Delta T_{MIN} = \frac{1.5 \times 10^{-3}}{0.1} = 0.015°C$$ ✓

(+3)

self heating?

$$\Delta T_{self} = \frac{i_s^2 R_T}{\delta} \rightarrow (.15 \times 10^{-3} A)^2 (407) = .0092mW$$

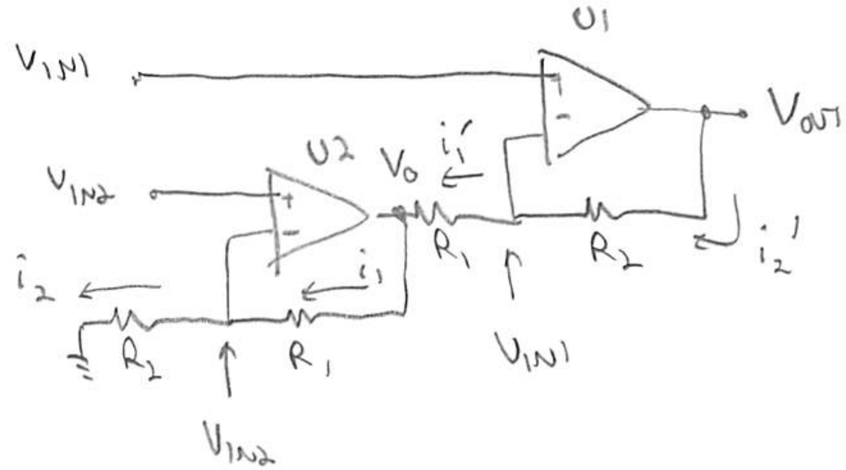
(+3)

$$\Delta T_{self} = \frac{.0092mW}{2mW/°C} = \underline{.0046°C} < \frac{.015}{2} = \underline{.0075°C}$$

$\Rightarrow$ **$A_d = 50$ works!**

(extra sheet for work)

(b)



• Start with U2:

$$i_2 = i_1$$

$$\frac{V_{IN2} - 0}{R_2} = \frac{V_0 - V_{IN2}}{R_1} \rightarrow \frac{R_1}{R_2} V_{IN} + V_{IN2} = V_0 = \left(1 + \frac{R_1}{R_2}\right) V_{IN2}$$

• Now do U1:

$$i_2' = i_1'$$

$$\frac{V_{OUT} - V_{IN1}}{R_2} = \frac{V_{IN1} - V_0}{R_1} \rightarrow V_{OUT} - V_{IN1} = \frac{R_2}{R_1} V_{IN1} - \frac{R_2}{R_1} V_0$$

$$V_{OUT} = \left(\frac{R_2}{R_1} + 1\right) V_{IN1} - \frac{R_2}{R_1}\left(1 + \frac{R_1}{R_2}\right) V_{IN2}$$

$$= \left(1 + \frac{R_2}{R_1}\right) V_{IN1} - \frac{\cancel{R_2}}{R_1} \frac{R_2 + R_1}{\cancel{R_2}} V_{IN2}$$

$$= \left(1 + \frac{R_2}{R_1}\right) V_{IN1} - \left(\frac{R_2}{R_1} + 1\right) V_{IN2}$$

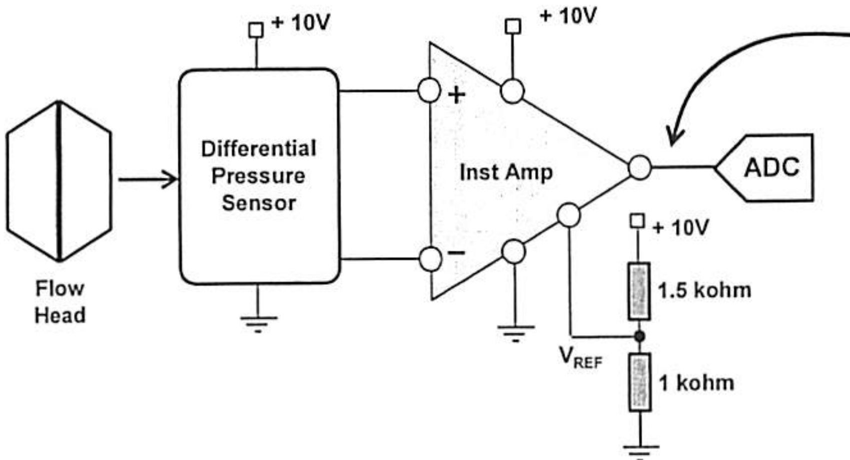
$$\boxed{V_{OUT} = \left(1 + \frac{R_2}{R_1}\right)\left(V_{IN1} - V_{IN2}\right)}$$

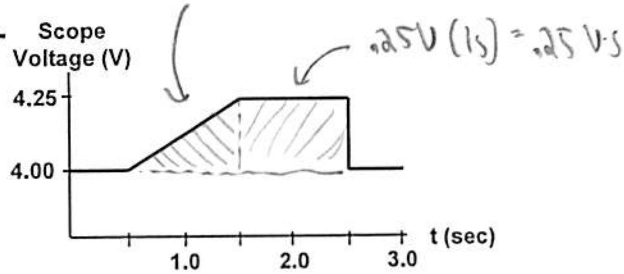
+5

Problem #4: Spirometer (20 pts)

You must design a flow spirometer system to measure a maximum flow of $+F_{MAX}$ = 25 L/s, $-F_{MAX}$ = -5 L/s, and a sensitivity of ΔF_{MIN} = 0.01 L/s. The instrumentation amplifier is powered by 10V and GND, so its output is limited to within 1 V of each power supply. The amplifier has Ad = 400 and V_N = 1 mV. The system is calibrated by injecting 3 liters of air. The scope waveform is shown below.

$\frac{1}{2}(.25V)(1s) = .125\ V\cdot s$





Total = .125 + .25

= .375 V·s

a) You have two ADCs available. ADC #1 has 12 bits from 0-to-10V while ADC #2 has 14 bits from 0-to-5V. Are all design requirements satisfied by one ADC, both ADCs, or neither ADC? Show all work!

b) You notice a 4.7 kohm resistor in your pocket. A gift from the heavens? Divine inspiration makes you wonder if the V_{REF} voltage divider needs to be modified. With the appropriate ADC, can all design requirements be satisfied if you replace the lower or upper resistor? You can re-use any relevant calculations from part (a).

c) In reality, the instrumentation amplifier has a non-zero common-mode gain A_{CM}. When there is no flow, both amplifier inputs are 5V. This common-mode input adds a slight error ΔF_{error} to the final flow measurement. What is the smallest amplifier CMRR to ensure that $\Delta F_{error} \leq 0.5\Delta F_{MIN}$ of the system? Express your answer in dB. Show all work!

(a) $V_M = 4 + A_d S R F$

$\int (V_M - 4)\,dt = A_d S R \int F\,dt$ → $SR = \frac{.375\ V\cdot s}{400 \cdot 3L} = 3.13\times10^{-4}\ V\cdot\frac{s}{L}$

(.375 V·s; 400; 3L)

$A_d S R = 400 \cdot (3.13\times10^{-4}) = .125\ V\cdot\frac{s}{L}$

$V_M = 4 + (.125\ V\cdot s/L)\cdot F$ (+4)

ADC1: $1 < V_M < 9$; $9 = 4 + .125(+F_{max})$ → $F_{max} = \frac{9-4}{.125} = 40\ L/s$ ✓

$\Delta V_{ADC} = \frac{10-0}{2^{12}-1} = 2.4\ mV$ $1 = 4 + .125(-F_{max})$ → $-F_{max} = \frac{1-4}{.125} = -24\ L/s$ ✓

(+2) → ΔV_{min} 2.4 mV $\Delta F_{min} = \frac{.0024\ V}{.125\ V\cdot s/L} = .0195\ L/s$ ✗ (Too big)

(extra sheet for work)

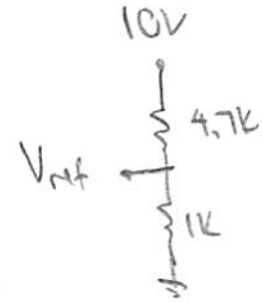
ADC2: $1 < V_M < 5V$: $F_{max} = \frac{5-4}{.125} = 8 \text{ L/s}$ X (Too small)

$\Delta V_{ADC} = \frac{5-0}{2^{14}-1} = .31 mV$ $\quad -F_{max} = \frac{1-4V}{.125 \text{ V·s/L}} = -24 \text{ L/s}$ ✓ (+4)

$\Delta F_{min} = \frac{.001V}{.125 \text{ V·s/L}} = .008 \text{ L/s}$ ✓ (+2)

Neither ADC works ☹

(b) Changing V_{ref} does not affect sensitivity.



ADC1 X

ADC2? Lower V_{ref} should help $+F_{max}$.

↳ $10V \cdot \frac{1K}{5.7K} = 1.754V$ (+4)

$+F_{max} = \frac{5-1.754V}{.125 \text{ V·s/L}} = 26.0 \text{ L/s}$ ✓

$\Delta F_{min} = .008 \text{ L/s}$ ✓

$-F_{max} = \frac{1-1.754}{.125} = -6.0 \text{ L/s}$ ✓

Change upper resistor! ☺

(c) $V_M = V_{ref} + A_d \underbrace{SRF}_{\Delta V} + A_{cm} V_{CM}$

$F = \frac{V_M - V_{ref} - A_{CM} V_{CM}}{A_d SR} = \frac{V_M - V_{ref}}{A_d SR} - \boxed{\frac{A_{CM} V_{CM}}{A_d SR}}$ ← ΔF_{error}

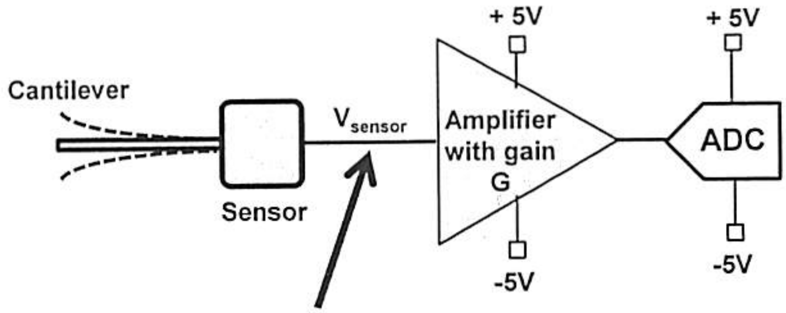
$\frac{A_{CM} 5V}{.125 \text{ V·s/L}} \le \overbrace{.004 \text{ L/s}}^{\frac{1}{2}\Delta F_{min}}$

$A_{CM} < .0001$

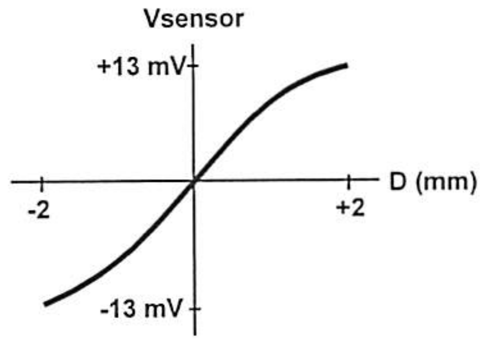
$CMRR > 20\log_{10}\left(\frac{400}{.0001}\right) = \boxed{132 \text{ dB}}$ (+4)

Problem #5: Vibration Measurement (20 pts)

You are asked to design a system to measure the displacement of a cantilever-type structure. The maximum expected displacement is D_{MAX} = +/- 2 mm, and the desired sensitivity is $|\Delta D_{MIN}|$ = 2 μm **over the entire measurement range.**



The sensor calibration curve is nonlinear, and can be fitted with a polynomial equation given by $V_{SENSOR} = aD - bD^3$, where a = 8 mV/mm and b = 0.4 mV/mm³.



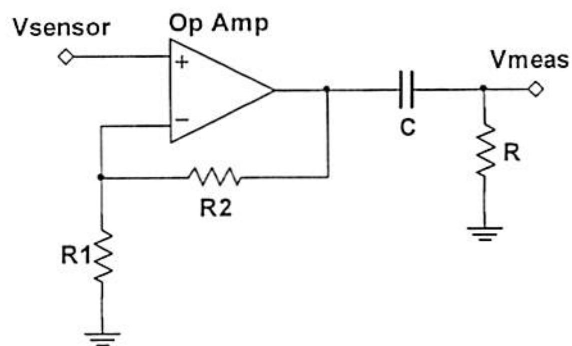
The amplifier is powered by +/- 5V. You can assume the amplifier output is limited to within 1V of each power supply. The ADC operates from -5V to +5V with 14 bits.

(a) You must choose between two amplifiers. Amplifier #1 has G = 300 and V_N = 3 mV, while amplifier #2 has G = 120 and V_N = 100 μV. Both amplifiers have Vref = 0V. Are all the design requirements satisfied by one, both, or neither amplifier? You must clearly explain why an amplifier works or doesn't work.

(b) Suppose we want to measure vibrations at frequencies over 10 Hz. Use the Golden Rules to show that the op amp circuit shown to the right produces:

$$\frac{V_{meas}}{V_{sensor}} = G\frac{jf/f_H}{1+jf/f_H}$$

NOTE: Clearly define G and f_H!



(c) At "very high" frequencies, $V_{meas}/V_{sensor} \approx G$. Assuming R1 = 1 kohm, what is an appropriate value for R2 to achieve a gain close to your answer to part (a)? Choose a standard 5% resistor (see table on last page).

(d) We want to suppress signal frequencies below 10 Hz. Suppose a frequency is "rejected" if $|V_{meas}/V_{sensor}|$ < 0.1G. Assuming R = 10 kohm, what is the appropriate value for capacitor C? Choose a standard 10% capacitor value (see table on last page). Show all work!

(a) $V_M = G V_{sensor}$ $-4V < V_M < 4V$

At $D = 2mm \Rightarrow V_{sensor} = \left(8\frac{mV}{mm}\right)(2mm) - \left(.4\frac{mV}{mm^3}\right)(2mm)^3 = 12.8mV$

symmetric for (+) vs. (−)

$G < \frac{4V}{.0128V} = 312.5$ ← Both G = 300 and 120 OK. (+6)

Sensitivity? $\Delta D_{min} = \frac{\Delta V_{min}}{\frac{\partial V_M}{\partial D}} = \frac{\Delta V_{MIN}}{G(a - 3bD^2)}$

$\Delta V_{ADC} = \frac{5 - -5}{2^{14}-1} = .61 mV$

(worst case)

(extra sheet for work) ΔD_{min} is largest when D is largest!

$$a - 3bD^2 = 8\,\frac{mV}{mm} - 3\left(.4\,\frac{mV}{mm^3}\right)(2\,mm)^2 = 3.2\,\frac{mV}{mm}$$

Amp 1: $V_N = 3\,mV > .61\,mV$

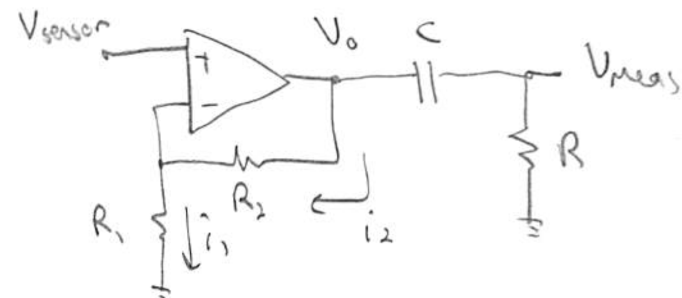
(+3) $\rightarrow \Delta D_{min} = \dfrac{3\,mV}{300\,(3.2\,mV/mm)} = .0031\,mm = 3.1\,\mu m$ X (Too big)

Amp 2: $V_N = 0.1\,mV < .61\,mV$

(+3) $\rightarrow \Delta D_{min} = \dfrac{0.61\,mV}{120\,(3.2\,mV/mm)} = .0016\,mm = 1.6\,\mu m$ ✓

Choose Amp 2

(b) $i_1 = i_2$



(+3) $\dfrac{V_{sensor} - 0}{R_1} = \dfrac{V_o - V_{sensor}}{R_2}$

$\dfrac{R_2}{R_1} V_s = V_o - V_s$

$V_o = \left(1 + \dfrac{R_2}{R_1}\right) V_s$

Next: $V_{meas} = V_o \dfrac{R}{R + \frac{1}{jwC}} = V_o \dfrac{RjwC}{RjwC + 1}$

$= V_o \dfrac{jwRC}{1 + jwRC} = \left(1 + \dfrac{R_2}{R_1}\right) \dfrac{j f/f_H}{1 + j f/f_H} V_s$

$\uparrow$

$\dfrac{1}{f_H} = 2\pi RC$

G

$\rightarrow$ $\boxed{\dfrac{V_{meas}}{V_{sensor}} = \left(1 + \dfrac{R_2}{R_1}\right) \dfrac{j f/f_H}{1 + j f/f_H},\quad f_H = \dfrac{1}{2\pi RC}}$

(extra sheet for work)

+2 (c) $G = 1 + \frac{R_2}{R_1} = 1 + \frac{R_2}{1K} = 120 \rightarrow R_2 = 119K$

Choose $\boxed{R_2 = 120K}$

(d) +3

Want $\frac{G \, f/f_H}{\sqrt{1+(f/f_H)^2}} \le 0.1 G$ @ 10Hz

$$\left(\frac{10}{f_H}\right) \le 0.1 \sqrt{1+(10/f_H)^2}$$

$$(10/f_H)^2 \le .01\left(1+(10/f_H)^2\right)$$

$$.99\,(10/f_H)^2 \le .01$$

$$\frac{10}{f_H} \le \sqrt{\frac{.01}{.99}} = 0.1$$

$$2\pi RC \cdot 10 \le .1$$

$$C \le \frac{0.1}{2\pi(10\times10^3)(10)} = 1.59\times10^{-7}\,F$$

$$= 159\,nF$$

Choose $\boxed{C = 150\,nF}$

Standard Resistor Values (±5%)						
1.0	10	100	1.0K	10K	100K	1.0M
1.1	11	110	1.1K	11K	110K	1.1M
1.2	12	120	1.2K	12K	120K	1.2M
1.3	13	130	1.3K	13K	130K	1.3M
1.5	15	150	1.5K	15K	150K	1.5M
1.6	16	160	1.6K	16K	160K	1.6M
1.8	18	180	1.8K	18K	180K	1.8M
2.0	20	200	2.0K	20K	200K	2.0M
2.2	22	220	2.2K	22K	220K	2.2M
2.4	24	240	2.4K	24K	240K	2.4M
2.7	27	270	2.7K	27K	270K	2.7M
3.0	30	300	3.0K	30K	300K	3.0M
3.3	33	330	3.3K	33K	330K	3.3M
3.6	36	360	3.6K	36K	360K	3.6M
3.9	39	390	3.9K	39K	390K	3.9M
4.3	43	430	4.3K	43K	430K	4.3M
4.7	47	470	4.7K	47K	470K	4.7M
5.1	51	510	5.1K	51K	510K	5.1M
5.6	56	560	5.6K	56K	560K	5.6M
6.2	62	620	6.2K	62K	620K	6.2M
6.8	68	680	6.8K	68K	680K	6.8M
7.5	75	750	7.5K	75K	750K	7.5M
8.2	82	820	8.2K	82K	820K	8.2M
9.1	91	910	9.1K	91K	910K	9.1M

Standard Capacitor Values (±10%)						
10pF	100pF	1000pF	.010μF	.10μF	1.0μF	10μF
12pF	120pF	1200pF	.012μF	.12μF	1.2μF	
15pF	150pF	1500pF	.015μF	.15μF	1.5μF	
18pF	180pF	1800pF	.018μF	.18μF	1.8μF	
22pF	220pF	2200pF	.022μF	.22μF	2.2μF	22μF
27pF	270pF	2700pF	.027μF	.27μF	2.7μF	
33pF	330pF	3300pF	.033μF	.33μF	3.3μF	33μF
39pF	390pF	3900pF	.039μF	.39μF	3.9μF	
47pF	470pF	4700pF	.047μF	.47μF	4.7μF	47uF
56pF	560pF	5600pF	.056μF	.56μF	5.6μF	
68pF	680pF	6800pF	.068μF	.68μF	6.8μF	
82pF	820pF	8200pF	.082μF	.82μF	8.2μF	