EECS 145L Final Examination Solutions (Fall 2004)

UNIVERSITY OF CALIFORNIA, BERKELEY
College of Engineering, Electrical Engineering and Computer Sciences Department

1.1 The **ideal op-amp amplifier** has (1) differential amplification (2) infinite gain at all frequencies (3) infinite input impedance (4) zero output impedance

[each of the four items was worth 2 points] [it was important to specify or show differential amplification because there is also a possible common mode gain, which is zero]

1.2 The **full-wave precision rectifier** has one input and one output. The output is equal to the absolute value of the input, even for very small (mV) input voltages.

[2 points off for not mentioning that it works for inputs < 0.6V, which distinguishes it from a full-wave rectifier that consists only of diodes; most students missed this one]

[2 points off for describing output for negative input only]

1.3 **PID control** is an algorithm that generates a control signal as a linear combination of the error signal P, its time integral I, and its time derivative D.

[3 points off for not mentioning the set point or error signal, which are essential for any control system]

[1 point off for not explaining the integral component of the control signal

[2 point off for not explaining the differential component of the control signal]

[2 point off for not explaining the proportional component of the control signal]

1.4 **The electromagnetic isolation amplifier** modulates the input signal with a high frequency carrier and transmits it to the output stage for demodulation. Transmission uses an air-core transformer that does not pass d.c. or 60 Hz.

1.5 **The thermistor** is a semiconducting temperature sensor whose resistance decreases with increasing temperature as $\exp(\beta/T)$

[2 points off for not stating which way the resistance changes with temperature]

2 The most straightforward solution was to isolate each 1 kHz and 2 kHz signal by using sharp n = 10 LPF and HPF in series. For a LPF with n = 10, the gain = 0.99 at f/fc = 0.823. For a HPF with n = 10, the gain = 0.99 at f/fc = 1.215.

The 1 kHz signal would be selectively passed by using a LPF with fc = 1.22 kHz in series with a HPF with fc = 0.823 kHz.

The 2 kHz signal would be selectively passed by using a LPF with fc = 2.44 kHz in series with a HPF with fc = 1.646 kHz.

[other high values of n were also accepted]

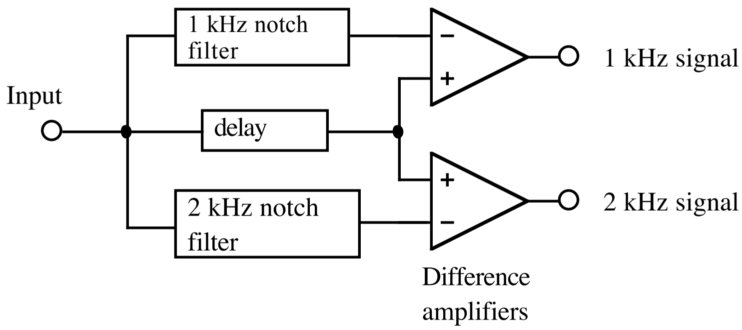
[8 points off for using LPF and HPF to separate the 1 kHz and 2 kHz signals from the 1 V p-p background but not separating them on separate outputs]

[6 points off for using a LPF to extract the 1 kHz signal and a HPF to extract the 2 kHz signal- this does not sufficiently remove the 1 V p-p background]

[16 points off for using a 1 kHz notch filter to generate signal 1 and a 2 kHz notch filter to generate signal 2- this results in useless signals that contain backgrounds and not the signals of interest]

Another solution was to use LPF ($f_c \approx 2.5$ kHz) and HPF ($f_c \approx 0.8$ kHz) to separate the 1 kHz to 2 kHz band from the total signal and then to use a 2 kHz notch filter to extract signal 1 and to use a 1 kHz notch filter to extract signal 2. This solution does not remove all of the background in the 1 to 2 kHz band, but was accepted for full credit.

The solution with the best background elimination removed the 1 kHz and 2 kHz signals with notch filters and subtracted the results from the original signal with difference amplifiers, as shown below.



[The delay compensates for the delay through the op-amps in the notch filters- it was not required for full credit]

[16 points off for using notch filters in a way that removes the 1 kHz and 2 kHz signals from the outputs]

3a Differential gain 1000, bandwidth 10 kHz

[3 points off for Gain = 10,000, bandwidth 1 kHz]

[3 points off for Gain = 100, bandwidth 100 kHz]

3b Output V_{rms} = (4 nV $Hz^{-1/2}$) (100 $Hz^{1/2}$) (1000) = 0.4 mV in 10 kHz

[2 points off for input noise rather than output noise]

[3 points off for not taking the square root of the bandwidth]

3c We want a Butterworth low-pass filter with a gain of G_1 = 0.99 at f_1 = 1 kHz and G_2 = 0.01 at f_2 = 2 kHz.

n	f_1/f_c	f_{c1}	f_2/f_c	f_{c2}	
6	0.723	1.383 kHz	2.154	0.929 kHz	fc1 > fc2; n too low
8	0.784	1.276 kHz	1.778	1.125 kHz	fc1 > fc2; n too low
10	0.823	1.215 kHz	1.585	1.262 kHz	fc1 < fc2; n =10 OK

The order is 10 and a corner frequency between 1.22 kHz and 1.26 kHz is OK. (order 12 also accepted)

[2 points off for order 8]

[4 points off if output noise not given or determined by multiplying the answer from 3b by 0.01 or 0.99]

After amplification and filtering, the output noise would be V_{rms} = (4 nV $Hz^{-1/2}$) sqrt(1.24 kHz) (1000) = (4 nV $Hz^{-1/2}$) (35.3 $Hz^{1/2}$) (1000) = 0.141 mV in 10 kHz

So the filtering reduced the output noise from ±0.4 mV to ±0.14 mV

3d The best way to reduce the 60 Hz interference from the middle of a band of frequencies of interest is to use a notch filter. The common mode rejection ratio of 60 dB means that the common mode gain is 1000/1000 = 1. So the instrumentation amplifier 60 Hz output will be ±10 mV from a common mode input of ±10 mV. The output due to a differential 60 Hz interference is (±0.01 mV) (1000) = ±10 mV. In the worst case, these are in phase, producing a total of ±20 mV. A notch filter can reduce this total by a factor of typically 30, to ±0.7 mV.

[Any value between 0.1 and 2 mV was accepted for full credit]

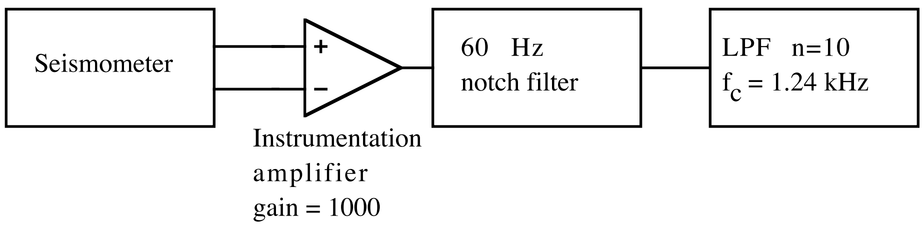
[2 points off for including one 10 mV and not the other]

[5 points off if input noise not given or not based on 60 Hz interference]

[5 points off if output noise not given]

[10 points off for using a HPF, which removes the important earthquake frequencies below 60 Hz]

3e [OK to reverse order of low pass and notch filters]



[4 points off if amplifier not in circuit]

4.1 Case $V_1 < 0$

op-amp has positive output so only D_1 conducts to close negative feedback loop

$V_2 = 0$ by virtual ground

$V_0 = -V_1$

$V_3 = -V_1 + 0.6$ V

[4 points off for $V_3 = V_1$] [4 points off for $V_3 = 0.6$V] [6 points off for $V_0 = 0$]

[6 points off for $V_2 \neq 0$] [6 points off for $|V_3| > V_1$] [6 points off for $V_3 = 0$]

4.2 Case $V_1 > 0$

op-amp has negative output so only D_2 conducts to close negative feedback loop

$V_2 = 0$ by virtual ground

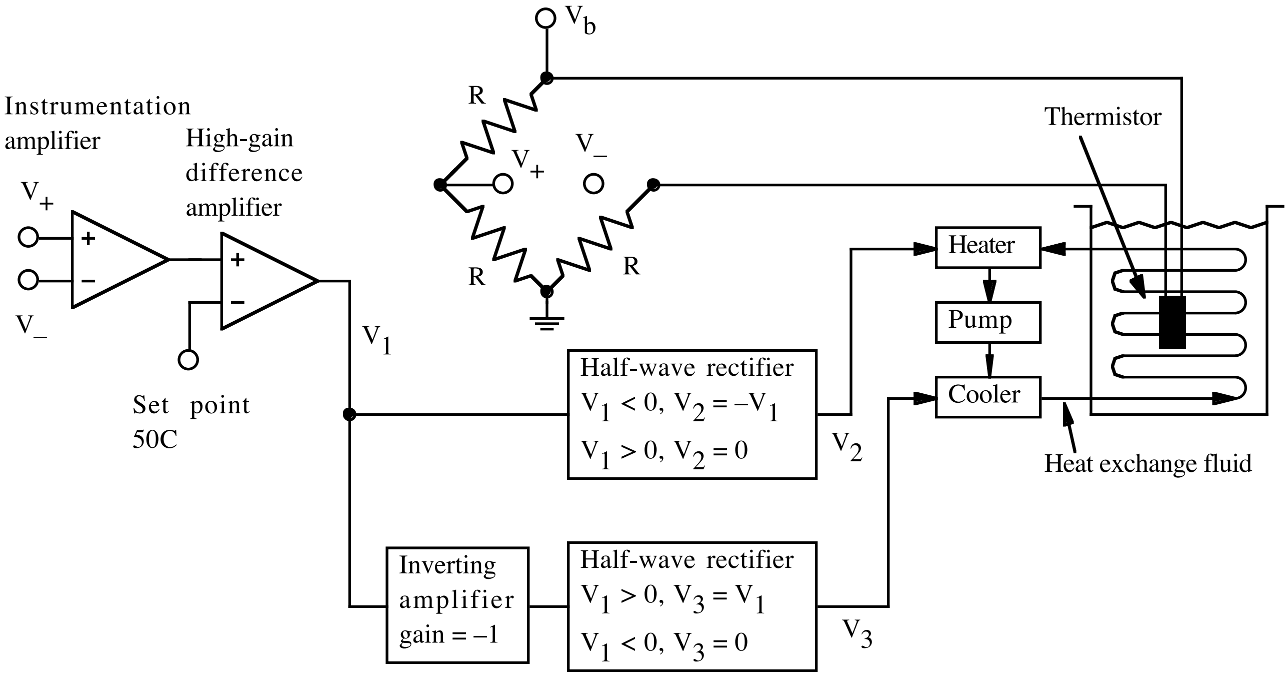
$V_0 = 0$ due to direct connection to V_2

$V_3 = -0.6$V

[2 points off for $V_3 = +0.6$V] [4 points off for $V_3 = 0$] [6 points off for $V_0 = \pm V_1$]

[6 points off for $V_2 \neq 0$] [6 points off if V_3 depends on V_1]

5a



If the thermistor is < 50C, $V_1 < 0$, $V_2 > 0$, $V_3 = 0$

If the thermistor is > 50C, $V_1 > 0$, $V_2 = 0$, $V_3 > 0$

The difference amplifier was not needed if the thermistor bridge was set for 0V output at 50C. This design makes it more difficult to change the set point, however.

5b

- Initially set point is changed to 50C, error signal V_1 is negative and heater is activated
- When temperature gets slightly above 50C, the error signal V_1 becomes positive, and the cooler turns on briefly to bring the temperature below 50C
- As chemical reaction proceeds, tanks heats above 50C, the error signal V_1 becomes positive, and the cooler turns to hold the temperature at 50C
- After the chemical reaction completes, error signal V_1 is negative and heater is activated to maintain 50C

145L FINAL EXAM GRADE STATISTICS

Problem	1	2	3	4	5	Total
Average	31.4	18.0	45.5	26.9	37.0	158.7
rms	4.8	7.7	6.7	12.4	7.6	22.5
Maximum	40	24	56	40	40	200

Total score distribution:

100-109 0	110-119 1	120-129 3
130-139 3	140-149 4	150-159 2
160-169 5	170-179 4	180-189 4
190-199 1	200 0	

145L COURSE GRADE STATISTICS

Grade	Undergraduate Scores	Graduate Scores
A+	944	
A	926, 933, 939	924
A–	892, 892, 895, 901, 906, 907, 908, 916	914
B+	872	877
B	830, 832, 837, 839, 840, 841	
B–	805	
C+	779, 781, 798	
C	765	
C–		
D+		
D		
D–		
F		
Maximum	1000	1000
Average	863.6	905.0
rms	55.0	24.8

Bioengineering undergraduate average = 865.8, rms = 32.7
EECS undergraduate average = 869.7, rms = 64.4

Note: the average grade for the lab report 4, 6, 12, 14 series was 87.5 and the average grade for the lab report 5, 11, 13, 15 series was 89.0. The difference was less than one standard deviation of the difference. No adjustment was necessary.