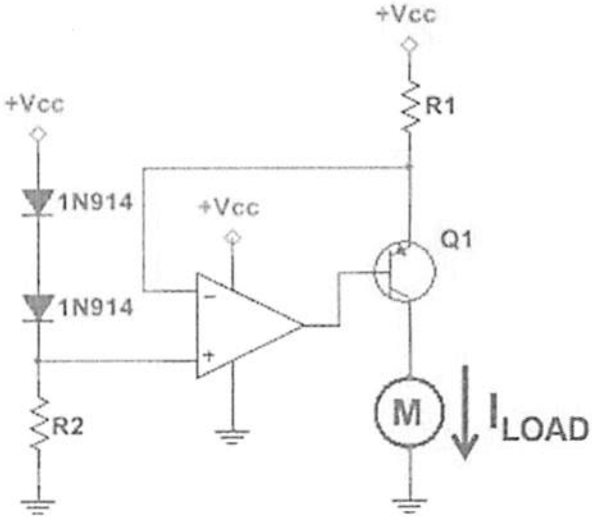
ECE 363 FINAL (F18) NAME: Solutions

6 problems for 100 pts

Problem #1: Constant Current Source (18 pts)

Suppose we need to drive a motor in constant torque mode, which means it needs a fixed current rather than a voltage. Consider the constant current source shown in the figure. It works like this: The op amp's (+) input is two diode drops below +Vcc. The Q1 emitter current depends on R1, while the load current comes from Q1's collector.



The design constraints are the following:

- The motor is rated at 200 mA @ 6V
- Vcc = 12V
- The op amp is an LF356
- The diodes are 1N914
- Q1 is either a 2N4403 or TIP30G
- R1 and R2 must be standard 5% resistors

4 (a) Assuming typical 1N914 conditions, choose the appropriate value for R2.

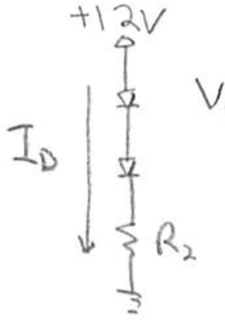
4 (b) Perform a "quick" analysis to choose Q1. You must explain why you chose one transistor and not the other!

4 (c) Choose R1, based on **typical Q1 conditions**.

3 (d) Show that the op amp can produce the required output voltage and current, even under **worst case Q1 conditions.**

3 (e) Suppose Vcc comes from a battery, which means Vcc will decrease as the battery is drained. What is the smallest value of Vcc that allows proper current source operation? Assume **worst-case Q1 conditions.**

ⓐ $I_D = \dfrac{12 - 2\times .62V}{R_2} = 1mA$



$V_F = .62V$ @ $1mA$

+4

$\rightarrow R_2 = 10.8K$

choose $\boxed{R_2 = 10K}$

ⓑ

	$\underline{\text{Max } I_C}$	$\underline{V_{CE}}$	$\underline{P_{max}\text{ (no HS)}}$	$\underline{P_{max}\text{ (w/ HS)}}$
2N4403	600mA ✓	40V ✓	.625W ✗	?
TIP 30	1A ✓	40V ✓	2W ✓	30W

$\Theta_{JC} = 83.3\,°C/W$

$$P = \frac{.2A}{101}(0.7V) + .2A\left[\underbrace{(12-2\times .62)-6}_{4.76V}\right] = \underline{0.953W} \xrightarrow{\times 2} \underline{\underline{1.91W}}$$

(extra sheet for work)

2N4403 : Heat sink?

$$25^\circ C + .953W \times (83.3 + .5 + \Theta_{SA}) < 85^\circ C$$

$$\rightarrow \underbrace{\Theta_{SA} < -20.8^\circ C/W}_{\frown} !$$

(+4)

$\Rightarrow$ Choose $\boxed{\text{TIP 30 (no HS needed)}}$

ⓒ TIP30: $\beta \sim 150$ $\quad I_C = .2A = \frac{150}{151} I_E = .993 \frac{2 \times .62V}{R_1}$

(+4)

$\rightarrow R_1 = 6.16\Omega$ Choose $\boxed{R_1 = 6.2\Omega}$

ⓓ TIP30: $\beta_{min} \sim 40 \rightarrow i_o = \frac{.2A}{41} = 4.9\,mA$

$|V_{BE}| \sim 1.3V \quad V_o = 12 - 2 \times .62 - 1.3V = \underline{9.46V}$

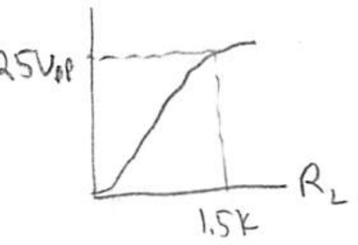
(+3)

$V_{cc} - V_o = 12 - 9.46 = \underline{\underline{2.54V}}$ ← Head room

For $V_{cc} = 15V \rightarrow \max V_o = 15 - 2.54 = 12.46V = 24.9\,V_{pp}$

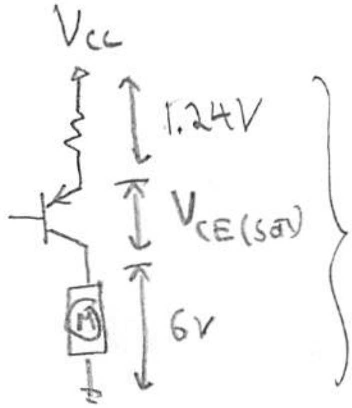
$i_o = \frac{12.5V}{1.5K} = \underline{\underline{8.3\,mA}}$ ✓

$\boxed{\text{YES}}$



ⓔ Must not saturate Q1!

(+3)



$V_{cc} > 1.24 + .7 + 6$

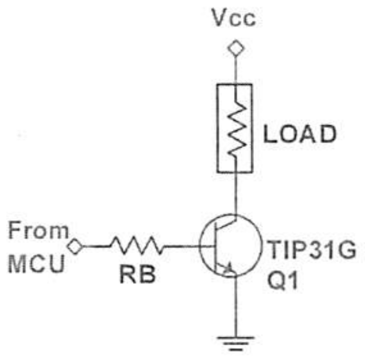
$> \boxed{7.94V}$ ←

(9.94V with 2V head room)

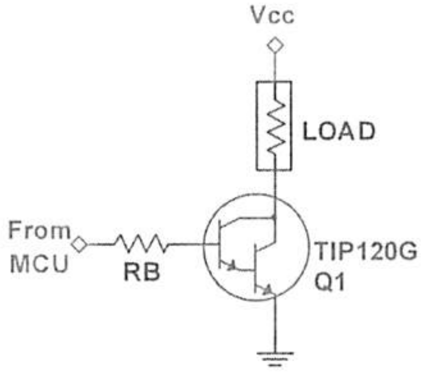
Problem #2: Muscle Wire Controller (18 pts)

Consider a robotics application involving "muscle wire", which is made of a special nickel-titanium alloy. Muscle wire requires electrical current to produce a contraction. The microcontroller, transistor switch, and muscle wire are all operated from the same V_{CC} = 3.5V power supply. From an electrical viewpoint, muscle wire is just a resistor. The design constraints are the following:

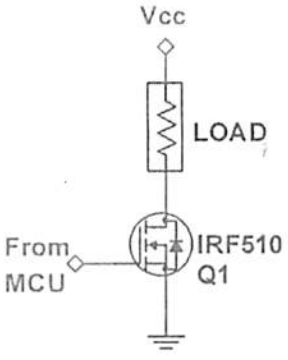
- Muscle wire rating is 1.5A @ 3.5V
- Microcontroller unit (MCU): 3.5V logic and max I_{OUT} = 20 mA
- Available transistors are: TIP31, TIP120, IRF510
- Any resistors must be standard 5% value.



#1



#2



#3

(a) Explain why Circuit #2 works while the other two do not.

(b) Assuming typical Q1 conditions, compute the load current and choose the appropriate value for RB.

(c) Assuming typical Q1 conditions, compute the power dissipation in the muscle wire.

(d) Assuming typical Q1 conditions, does Q1 need a heat sink?

X

ⓐ Circuit #1: $I_B \sim \frac{1.5A}{10} = 150mA > 20mA$ current limit of MCU

Circuit #2: $I_B \sim \frac{1.5A}{250} = 6mA < 20mA$ ✓

+4

Circuit #3: $\underbrace{V_{GS,TH} = 4V\ (max)}_{Q_1 \text{ will never turn ON!}} > 3.5V$ logic X

ⓑ TIP120: $\left.\begin{array}{l} V_{CE(sat)} = 0.9V \\ V_{BE(sat)} = 1.55V \end{array}\right\}$ @1.5A

$R_L = \frac{3.5V}{1.5A} = \underline{\underline{2.33\Omega}}$

$I_L = \frac{3.5 - .9}{2.33\Omega} = \boxed{1.12A}$

+3

(extra sheet for work)

$$I_B \sim \overbrace{\frac{1.12A}{250}}^{4.5mA} = \frac{3.5 - \overset{V_{BE}@1A}{1.5}}{R_B} \rightarrow R_B = 446.4\Omega \quad \boxed{\text{Choose } R_B = 430\Omega}$$

+3

ⓒ $P = I_L^2 R_L = (1.12A)^2(2.33\Omega) = \boxed{2.92W}$

+3

ⓓ $I_B = \frac{3.5-1.5}{430\Omega} = 5mA$

$$P = (.005A)(1.5V) + (1.12A)(\overset{V_{CE}@1A}{0.85V}) = 0.96W \xrightarrow{\times 2} \underline{\underline{1.92W}}$$

TIP120: $P_{max} = 2W$ (no HS)

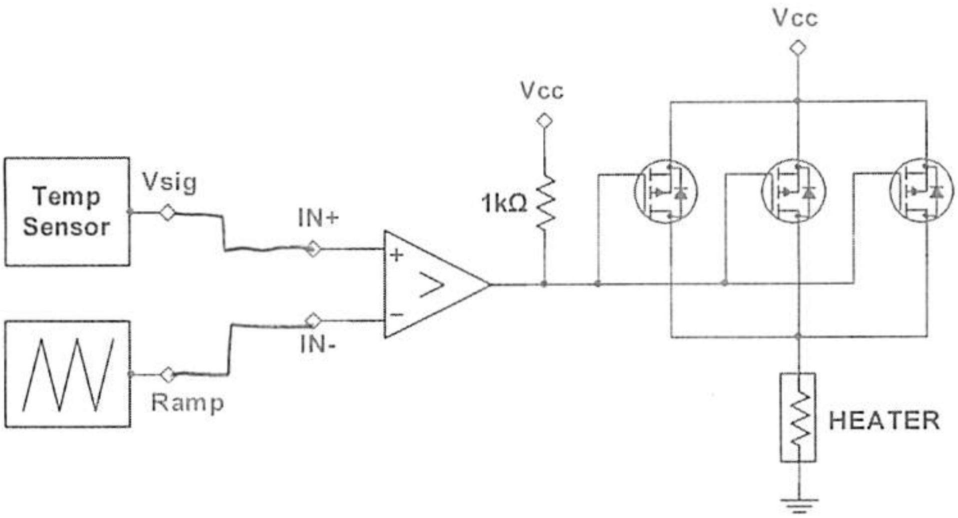
$\Rightarrow$ NO heat sink needed! ☺

+5

Problem #3: Heater Controller (18 pts)

You are asked to design a heating system for an egg incubator. The heater is operated with a PWM controller. If the temperature drops below T_{MIN} = 35°C, then the heater should be on all the time. If the temperature rises above T_{MAX} = 40°C, then the heater should be completely off. The design constraints are the following:

- Temp sensor: Vsig increases with temperature (Vsig = 1V for T_{MIN} = 35°C; Vsig = 3V for T_{MAX} = 40°C).
- The ramp waveform goes from 1 to 3V at 2 kHz.
- V_{CC} = 15V
- Heater is rated at 15V @ 18W and driven by three parallel IRFD9210 p-channel MOSFETs



(a) Explain the rationale for how would you connect Vsig and Ramp to the comparator.

(b) Assuming the heater is always ON, do the MOSFETs need heat sinks? Assume all three MOSFETs have identical $R_{DS,ON}$ and assume typical transistor conditions. Show all work!

(c) Suppose Vsig = 1.5V. Sketch the ramp waveform, comparator output, and the heater current over a 2 ms interval. Label your axes and important features!

ⓐ Cold (Low Vsig) → Comparator Output Low → Heater ON

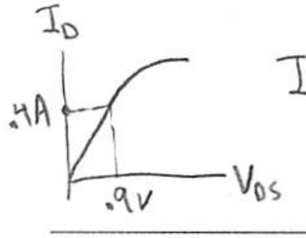
Vsig > Ramp ? NO ⟹ $\boxed{\begin{array}{l} V_{sig} \rightarrow IN(+) \\ Ramp \rightarrow IN(-) \end{array}}$

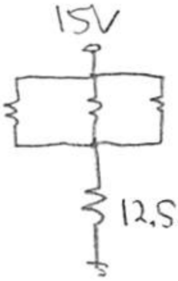
+4

ⓑ Heater: $\frac{V^2}{R} = P \rightarrow R_L = \frac{(15V)^2}{18W} = 12.5\Omega$

$I = \frac{15V}{12.5\Omega} = 1.2A$ ←

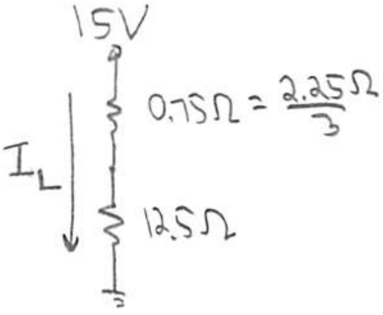
Each MOSFET has ~ 0.4A





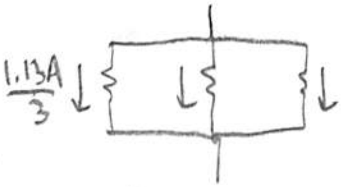
$R_{DS,ON} = \frac{.9V}{.4A} = 2.25\Omega$

(extra sheet for work)



+3

$$I_L = \frac{15-0}{.75+12.5} = \underline{\underline{1.13A}}$$



So, each MOSFET has $P = \left(\frac{1.13A}{3}\right)^2 (2.25\Omega)$

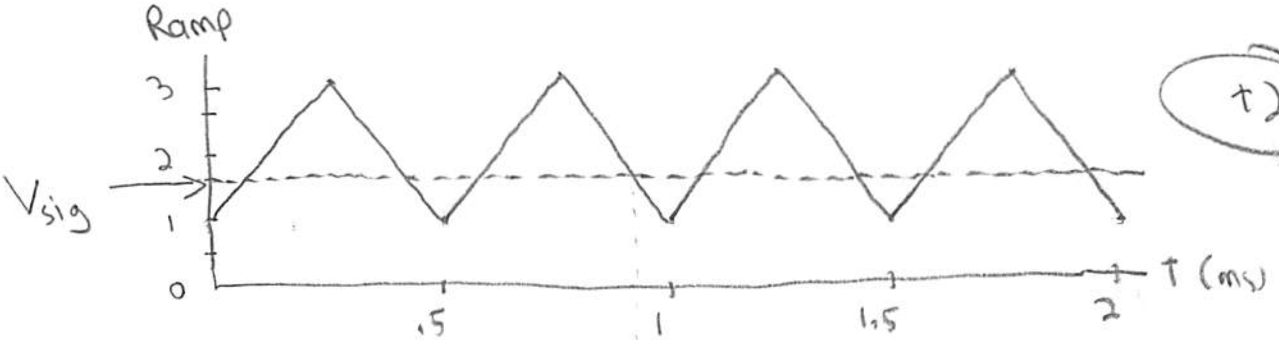
$= \underline{\underline{0.32W}} \xrightarrow{\times 2} 0.64W$

IRFD 9210: $P_{max} = 1W$ (no HS)

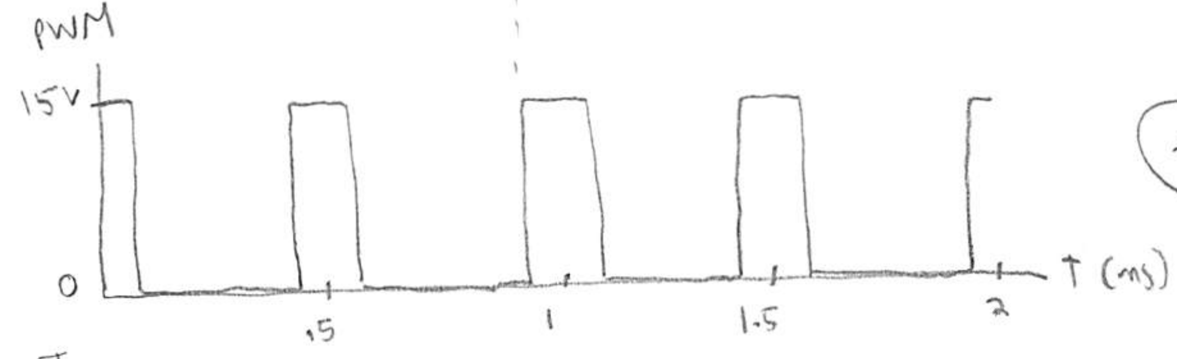
No HS needed! :)

+3

(c) 2kHz → 1 cycle = .5ms



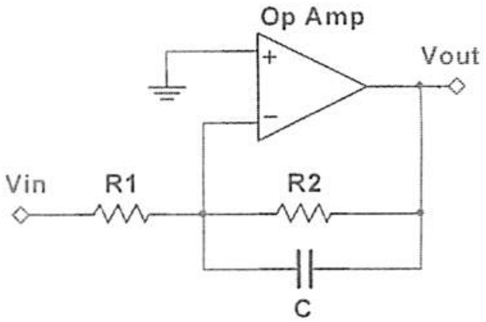
+2



+3

+3

Problem #4: Inverting Amplifier + Low-pass Filter (18 pts)



The circuit to the right combines an inverting amplifier with a low-pass filter. The amplifier gain is $V_{OUT}/V_{IN} = -R2/R1$ at DC. However, the capacitor causes $|V_{OUT}/V_{IN}|$ to decrease with higher frequency.

Suppose the design requirements are the following:

- $|G| = 40$ dB at DC
- $|G| = 0$ dB (+/- 1 dB) at 40 kHz
- Input impedance $Z_{IN} \geq 10$ kohm
- Use only standard 5% resistors and 10% capacitors.

(a) Use the Golden Rules to show that:

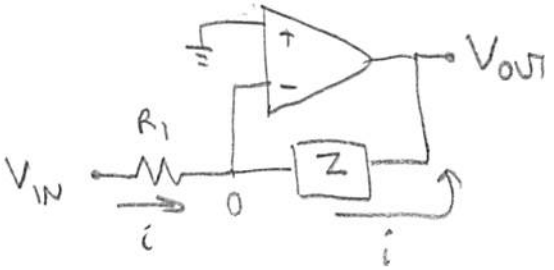
$$|G| = \left|\frac{V_{OUT}}{V_{IN}}\right| = \frac{R_2}{R_1}\frac{1}{\sqrt{1+(f/f_C)^2}}$$

Make sure to clearly derive the cut-off frequency f_C!

(b) Choose the appropriate values for R1, R2, and C. You must clearly show that the design specs have been satisfied!

(c) Suppose $V_{IN} = 0.05 + 0.5\sin(2\pi f_0 t)$, where $f_0 = 40$ kHz. Sketch both V_{IN} and V_{OUT} over a 75 us interval. Label all axes and important features!

ⓐ $i = \frac{V_{IN}-0}{R_1} = \frac{0-V_{OUT}}{Z}$



$$\frac{V_{OUT}}{V_{IN}} = -\frac{Z}{R_1} = -\frac{R_2\frac{1}{j\omega C}}{R_1\left(R_2+\frac{1}{j\omega C}\right)}$$

+6

$$= -\frac{R_2}{R_1}\frac{1}{1+j\omega R_2 C} = -\frac{R_2}{R_1}\frac{1}{1+jf\cdot\underbrace{2\pi R_2 C}_{1/f_c}} = -\frac{R_2}{R_1}\frac{1}{1+jf/f_c}$$

$$\Rightarrow \boxed{\left|\frac{V_{OUT}}{V_{IN}}\right| = \frac{R_2}{R_1}\frac{1}{\sqrt{1+(f/f_c)^2}}} \leftarrow f_c = \frac{1}{2\pi R_2 C}$$

ⓑ $Z_{IN} = R_1 \geq 10K$ Choose $\boxed{R_1 = 11K}$ ✓

$|G_0| = 10^{40/20} = 100 = \frac{R_2}{11K} \rightarrow \boxed{R_2 = 1.1M}$

$\uparrow$

+4 $|G_0| = \frac{1100}{11} = 100 = 40dB$ ✓

$$|G| = \frac{1100}{11}\frac{1}{\sqrt{1+(f/f_c)^2}} = 10^0 = 1$$

$$10^4 = 1+(f/f_c)^2$$

$$\sqrt{10^4-1} = f/f_c$$

(extra sheet for work)

$$f_c = \frac{40\times10^3}{\sqrt{9999}} = 400.02\text{ Hz} = \frac{1}{2\pi R_2 C} \Longrightarrow C = \frac{1}{2\pi R_2(400)} = 3.6\times10^{-10}\text{ F} = .36\text{ nF}$$

Choose $\boxed{C = 330\text{ pF}}$

↑ 390pF also OK

(+3)

$$\to f_c = \frac{1}{2\pi(1.1\times10^6)(330\times10^{-12})} = 438.4\text{ Hz}$$

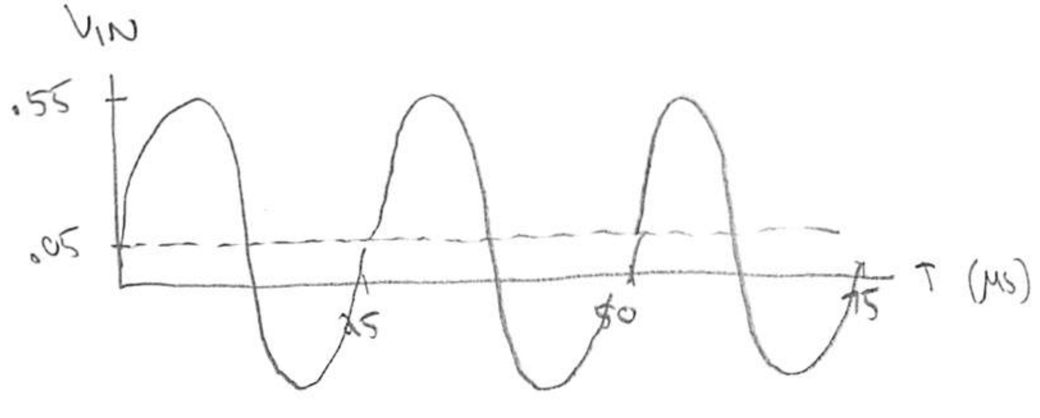
$$|G| = 100\frac{1}{\sqrt{1+\left(\frac{40000}{438.4}\right)^2}} = 1.1 = 0.8\text{ dB}$$ ✓ within 1dB of 0dB

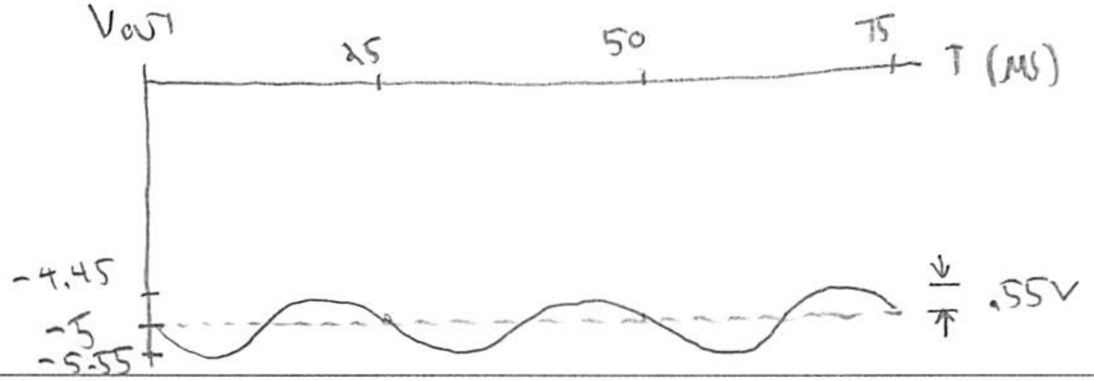
ⓒ $V_{IN} = \underset{\underset{\text{Gain}=-100}{\uparrow}}{\underset{\text{DC}}{\uparrow}}{.05} + \underbrace{.5\sin 2\pi f_o t}_{\text{40 kHz signal}} \Longrightarrow V_{OUT} = -5 - .55\sin 2\pi f_o t$

↖ Gain = −1.1

40kHz → 25μs = 1 cycle

(+5)

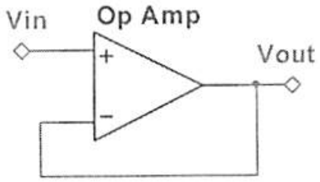




Technically, this should be more like a cosine due to phase of V_{OUT}/V_{IN}

Problem #5: Negative Feedback (14 pts)

Consider a voltage buffer using an op amp with Ri = 200 kohm and Ro = 150 ohm. The design requirements are the following:



- Closed-loop gain is no lower than 0.1% below G = 1.
- Input impedance $Z_{IN} \geq 1$ Gohm
- Output impedance $Z_{OUT} \leq 20$ milliohm

(a) Assuming an ideal op amp, what is the value of β?

(b) What is the minimum acceptable open-loop gain A_O of the op amp? Remember that you must satisfy all three requirements!

(c) Would the LF356 op amp be acceptable even under worst-case conditions? Show all work!

(d) Suppose Vin comes from a sensor with a source impedance of Z_S = 50 kohm. Sketch a modified circuit that minimizes output voltage error.

ⓐ Buffer: $G = 1 = \frac{1}{\beta} \rightarrow \boxed{\beta = 1}$ +2

ⓑ $G_{min} = \frac{A_{min}}{1 + A_{min}\beta} = \frac{A_{min}}{1 + A_{min}} = 1 - .001 = .999$

$A_{min} = .999 + .999 A_{min} \rightarrow A_{min} = \underline{\underline{999}}$

+7

$Z_{IN} = (1 + A_{min}\beta)(200K) \geq 10^9 \Omega$

$1 + A_{min} \geq \frac{10^9}{2\times10^5} \rightarrow A_{min} \geq \underline{\underline{4999}}$

Satisfies all 3 requirements!
↓

$Z_{OUT} = \frac{150\Omega}{1 + A_{min}\beta} \leq .020\Omega \rightarrow \frac{150}{.02} \leq 1 + A_{min} \Rightarrow \boxed{A_{min} > 7499}$

ⓒ LF356: $A_{min} = 25 \frac{V}{mV} = 25000 \; (T_A = 25°C)$
$15 \frac{V}{mV} = 15000$ (over temp)

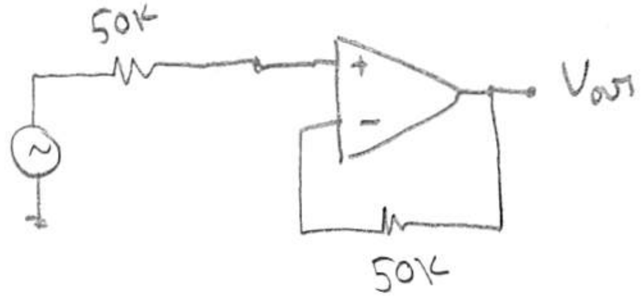
Both > 7499 ✓
YES, LF356 is good!

+2

(extra sheet for work)

ⓓ Match $R_{TH(-)}$ and $R_{TH(+)}$

+3



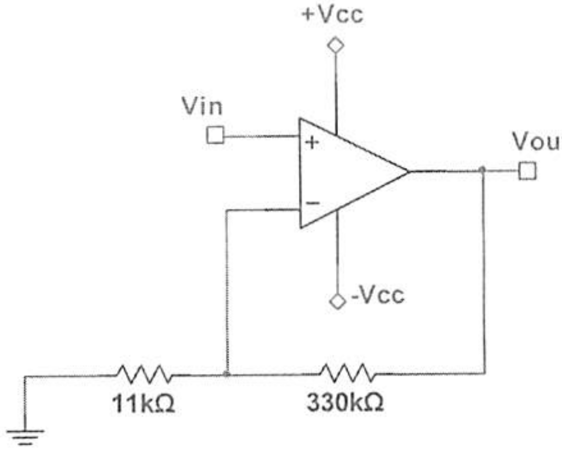
Problem #6: Amplifier Stability (14 pts)

Consider the non-inverting amplifier shown to the right. The op amp has an open-loop DC gain of 10 V/mV and poles at 30 kHz and 30 MHz.

a) Sketch the Bode plots for the magnitude and phase of the open-loop gain from 3 Hz out to 300 MHz. Label important features!

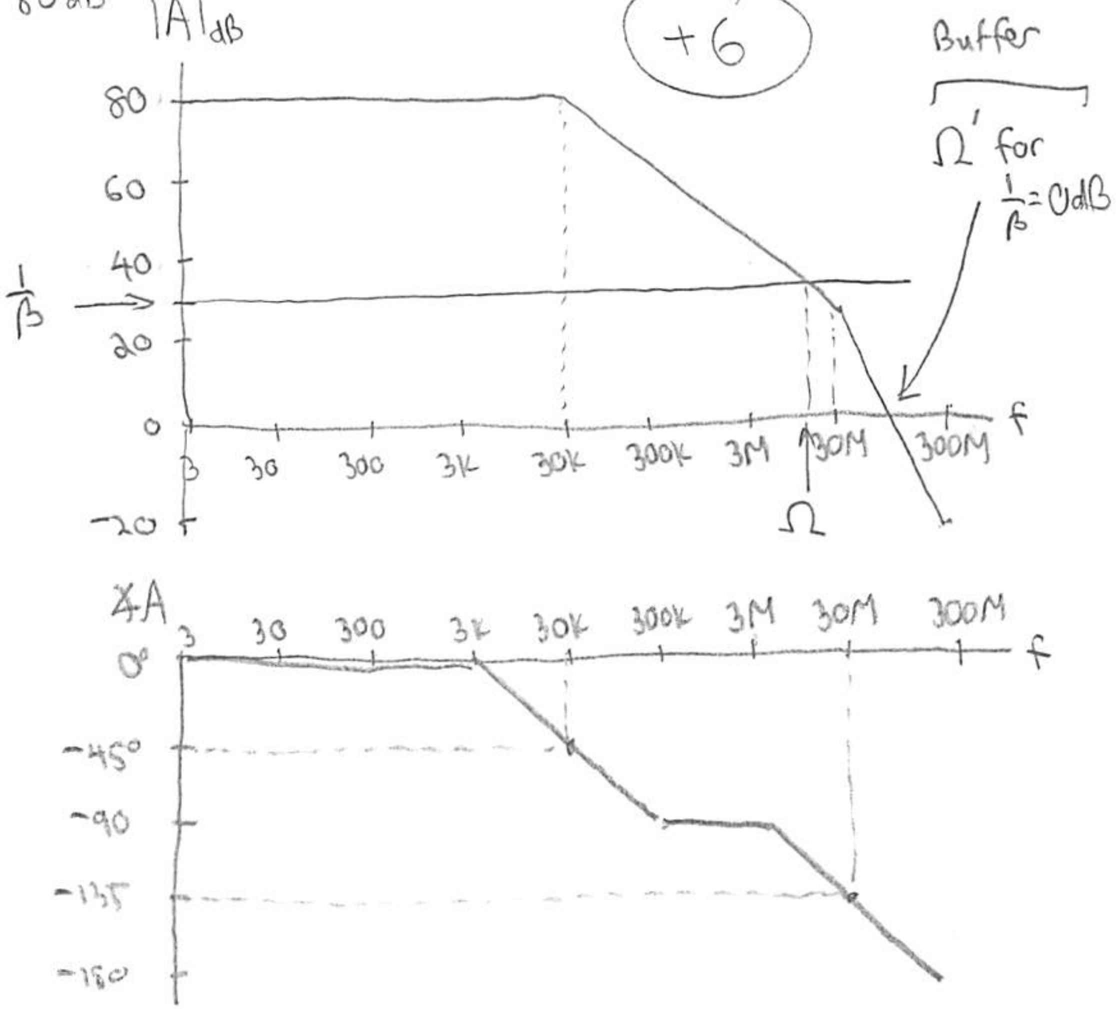
b) On your Bode plot for |A|, sketch 1/β and explain if the amplifier is stable or not.

c) Suppose you want to make a buffer. Compute the phase margin of the buffer and explain if it is stable or not.



ⓐ $10\frac{V}{mV} = 10^4 \rightarrow 80\,dB$

+6



ⓑ

$\beta = \frac{11K}{11K + 330K}$

$= .032$

$\frac{1}{\beta} = 31$

$= 29.83\,dB$

+3 $\sim 30\,dB$

$\Omega < f_{p2} = 30M$

$\Rightarrow$ $\boxed{\text{STABLE}}$!

ⓒ Buffer means

$G = \frac{10^4}{1 + 10^4\beta} = 1 \rightarrow \beta = \frac{10^4 - 1}{10^4} = 1 = \underline{\underline{0\,dB}}$ $\quad \Omega' = 30M \times 10^{.5\,\text{decade}} = \underline{\underline{94.9\,MHz}}$

Greater than f_{p2}! :(

(extra sheet for work)

$$\measuredangle A = -\tan^{-1}\left(\frac{94.9\times10^6}{30\times10^3}\right) - \tan^{-1}\left(\frac{94.9\times10^6}{30\times10^6}\right)$$

$$= -89{,}982^\circ - 72.457^\circ = -162{,}44^\circ$$

$$\text{Phase margin} = (-162{,}44^\circ) - (-180^\circ)$$

$$= \boxed{17{,}56^\circ} < 45^\circ$$

+5

$\Rightarrow$ unstable!

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	