Homework-4 Solutions

Note: I used $k_n = \mu_n C_{ox} \frac{W}{L}$

$k'_n = \mu_n C_{ox}$, $I_D = \frac{1}{2} k_n (V_{GS} - V_{TH})^2$

notation. Even you use a different notation, I won't downgrade your solution. Do not worry about it. However, some metrics such as efficency should be same.

1-a) M_1 behaves as a current source: It operates in saturation region and $V_{GS1} = 0$.

$$I_{D1} = \frac{1}{2} k_n (V_{GS} - V_{TH})^2$$

$$= \frac{1}{2} \, 12\,mA/V^2 (1.8)^2 V^2$$

$$= 19.44\,mA$$

→ For $R_L = \infty$, the max. output voltage depends on Q_1. Q_1 should not leave the forward operating region.

$$\boxed{V_{O\,MAX} = 5V - V_{CESAT\,Q1} = 4.8V}$$

$V_{O\,min}$ is about M_1. There are two scenarios. 1) M_1 should not leave saturation region.

2) M_1 should sink all the current on R_L.

- One of these two factors limits the minimum voltage.

Since $R_L = \infty$, it does not have any current. We should check the first scenario.

$$V_{DM1\,min} = V_{G2} - V_{THM1}$$
$$= -5V - (-1.8V) = -3.2V$$

So $\rightarrow$ $\boxed{V_{out\,min} = -3.2V}$

$\rightarrow$ For $R_L = 500\,\Omega$

V_{omax} is the same as it only depends on Q_1.

$$\boxed{V_{omax} = 4.8V}$$

Let's check the scenario-2 for

$R_L = 0.5k\Omega$

Question → Can M_1 sink all the current which flows through R_L = ?

$I_{M1} = 19.44\ mA$

↳ if all of this current flows through R_L,

$V_{RL} = 0 - 19.44mA \times 0.5k$
$= -9.72\ V$

we cannot go beyond this voltage, however our limiting factor in scenario-1 was worse. Thus,

$$\boxed{V_{out\,min} = -3.2V \text{ again!}}$$

1-b) we know that for the positive output voltage we can go up to 4.8V
Thus, 2V positive peak won't be problematic.

For the negative side M1 should sink the current. (should provide the necessary current)

$V_{out} = -2V = 0 - R_{Lmin} \times 19.44mA$

↳ our constant current on M1

$$\boxed{R_{L,min} = \frac{2V}{19.44mA} \cong 103\ ohm}$$

→ we cannot use a load resistor smaller than 103 ohm, if we want to -2V output signal at the output!

1-c) For the efficiency,

Load Power, $P_L = \frac{(|V_{out\,max}| / \sqrt{2})^2}{R_L}$

$V_{out\,MAX} = 2V$

$P_L = \frac{(2/\sqrt{2})^2}{R_L} \approx 19.4\,mW$

The rms voltage is $V_{peak}/\sqrt{2}$

what is supply power?

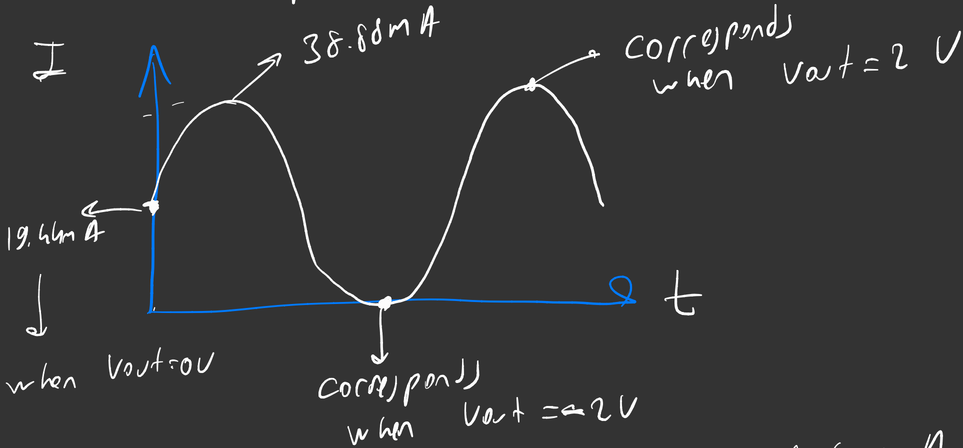
From negative supply, we are consuming constant M_1 current 19.44 mA.

P_S (from $-5V$) $= 19.44mA \times 5V = 97.2\,mW$

the current consumption from positive supply

↓

Let's plot the graph



Average current = 19.44 mA

thus,

P_s (from 5V) = 97.2 mW (also)

Total power consumption from supplies

$P_{s\,TOTAL} = 194.4\,mW$

$$\boxed{\eta = \frac{\text{Load Power}}{\text{supply power}} = \frac{19.4\,mW}{194.4\,mW} \approx 0.10}$$

2) The question is a little bit tricky.

a) For $V_i = 0$, $V_{EQ1} = 0.7V$,

$V_{EQ1} = V_{BQ3}$

$V_o = V_{BQ3} - V_{BEQ3} = 0V$

$I_{RL} = 0A$

so $I_{EQ3} = I_{EQ4}$

The transistors are matched and if they have the same V_{BE}, they also should have the same current, in quiescent conditions.

Then, $I_{EQ3} = I_{EQ2}$

$I_{EQ1} = I_{EQ4}$

Since $I_{EQ3} = I_{EQ4}$

$\rightarrow$ $I_{EQ1} = I_{EQ2} = I_{EQ3} = I_{EQ4}$

$$I_{R1} = \frac{V^{+} - V_{BE3}}{R_1} = \frac{12-0.7}{250} = 45.2\,mA$$

$\rightarrow$ $I_{B3} + I_{E1} = 45.2\,mA$

$\beta = 40$ $\quad (I_{B1}=I_{B2}=I_{B3}=I_{B4})$

$$\frac{I_{E1}}{41} + I_{E1} = 45.2\,mA$$

$$I_{E1} \cong 44.1\,mA$$

$$I_{B1} \cong 1.1\,mA$$

$$I_{E1} = I_{E2} = 44.1\,mA = I_{E3} = I_{E4}$$

$$I_{B1} = I_{B2} = 1.1\,mA = I_{B3} = I_{B4}$$

Observe that for class AB operation, output stage quiescent currents are not zero as opposite of class B!

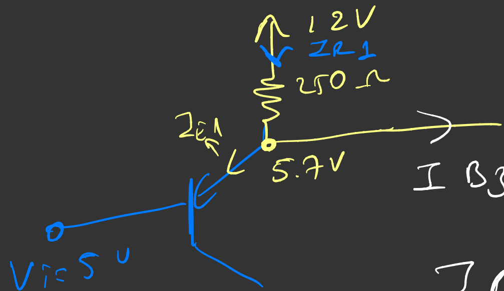
2-b) For $V_i = 5V$, we can neglect the current of Q_4 since it will be much smaller than Q_3.

V_o will track V_i due to Q_1, Q_3 configuration, thus

$V_i = 5V = V_o$, $i_o = \frac{5V}{8\Omega} = 0.625A$

All of this current through R_L, will be provided by Q_3, thus

$I_{E3} = 0.625A$, $I_{B3} \cong 15.25mA$



$I_{B3} = 15.25mA$

$I_{R1} = I_{B3} + I_{E1}$

$$I_{R1} = \frac{12V - 5.7V}{250} = 15.25mA + I_{E1}$$

$I_{E1} \approx 10mA$, $I_{B1} \approx 244\mu A$

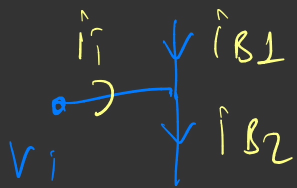
Since $I_{Q4} \approx 0$, $I_{BQ4} \approx 0$

All of the current through R_2 flows from I_{E2},

$$I_{E2} = I_{R2} = \frac{(4.3V) - (-12V)}{250\Omega} = 65.2mA$$

$$I_{B2} = \frac{65.2mA}{41} \approx 1.59mA$$

So what is the current drawn from the V_i ?



$$i_i = i_{B2} - i_{B1}$$
$$= 1.59mA - 0.244mA$$
$$= \underline{1.346mA}$$

Notes for 2-b

- The exact solution should be employed using exponential equations, however it is so complicated, This solution is not exact but gives what we need.

2-c) Current gain $= \boxed{\dfrac{i_o}{i_i} = \dfrac{625mA}{1.346mA} \cong 464 \dfrac{A}{A}}$

3) a) $V_i = V_{G2} = -1.5V$

$V_o = V_{S2} = 0V$

so $V_{GS_2} = -1.5V$

$$I_{D_2} = \frac{1}{2} k'p \frac{W_2}{L_2} \left(|V_{GS_2}| - |V_{TH_2}| \right)^2$$

$$0.5\,m\cancel{A}^{10^3} = \frac{1}{2}\, 40 \frac{\mu A}{\cancel{V^2}} \cdot \left(\frac{W}{L}_2\right) (0.7)^2 \cancel{V^2}$$

$$\boxed{\frac{W}{L}_2 = \frac{500 \times 2}{40 \times 0.49} \simeq 51}$$

$V_{GS1} = |V_{GS2}| = 1.5V$, thus

$V_{G1} = V_{G3} = 1.5V$, $V_{GS3} = |V_{GS4}|$

$V_{G3} - V_{GS_3} - |V_{GS4}| = V_I = -1.5V$

so $V_{GS3} = |V_{GS4}| = 1.5V$

$$\frac{\frac{W}{L}(1)}{\frac{W}{L}(2)} = \frac{k'p}{k'n}$$

(since I_D and V_{GS} are the same)

$$\boxed{\frac{W}{L}_1 = 20.4}$$

Since $V_{GS1} = |V_{GS2}| = V_{GS3} = |V_{GS4}|$

we easily can find $\frac{W}{L}(3)$ and $\frac{W}{L}(4)$

$$\frac{\frac{W}{L}B1}{\frac{W}{L}(1)} = \frac{I_{BIAS}}{I_{D1}} = \frac{0.2\ mA}{0.5\ mA} = \frac{2}{5}$$

$$\boxed{\frac{W}{L}3 = 8.16}$$

$$\frac{\frac{W}{L}(4)}{\frac{W}{L}(2)} = \frac{I_{BIAS}}{I_{D2}} = \frac{2}{5}, \quad \boxed{\frac{W}{L}4 = 20.4}$$

3-b) $V_{OMAX} = \min\left[\begin{array}{l}(V^+ - V_{OV1}),\\ V_{G3} - V_{GS1}\end{array}\right]$

since $V_{G3} < V^+$ and $V_{OV1} < V_{GS1}$

the worst case scenario,

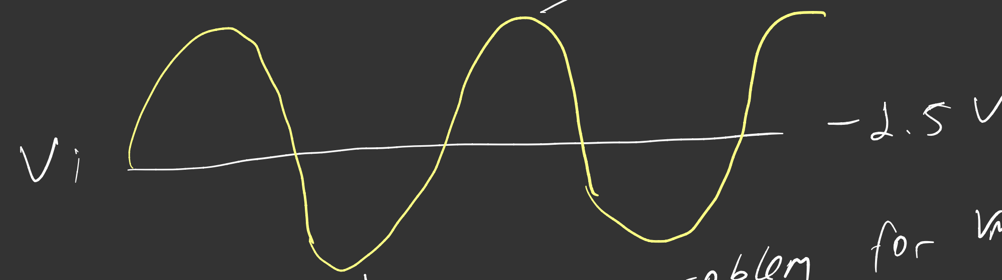
$V_{OMAX} = V_{G3} - V_{GS1}$

$= \boxed{10V - \underbrace{0.2V}_{\text{voltage drop on } Z_{BIAS}} - V_{GS1} = 8.3V}$

It is not the exact result, as while Vo increases I_{CC} will increase, I_{D1} will increase and V_{GS1} will be larger than 1.5V. However, we can assume V_{GS} is constant for a quick observation.

For minimum Vout, let's assume Vi as given below, for

this is problem for vomax



this is problem for Vmin

when we decrease Vi, there is no problem for M_n as it always operates at saturation region. However, M_2 may leave the saturation region.

$$V_{G2} - V_{THP} \geq -10V$$

so

$$V_{G2} > -10.8V$$

$$V_{o2} > -9.3V$$

$$\boxed{V_{o2min} = -9.3V}$$

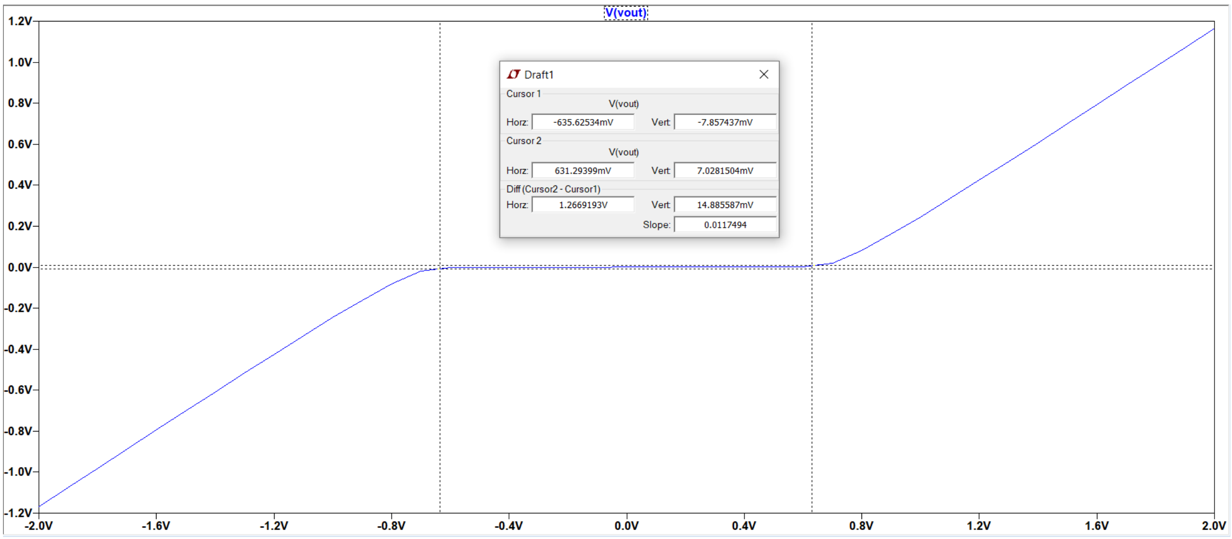
Important Note

For the positive side I_{BIAS} limits our operation. It is a current source and should not leave saturation. This is why we cannot go beyond 9.8V at V_{G1}. However, for the negative side, there is nothing which limits us except M2 transistor.

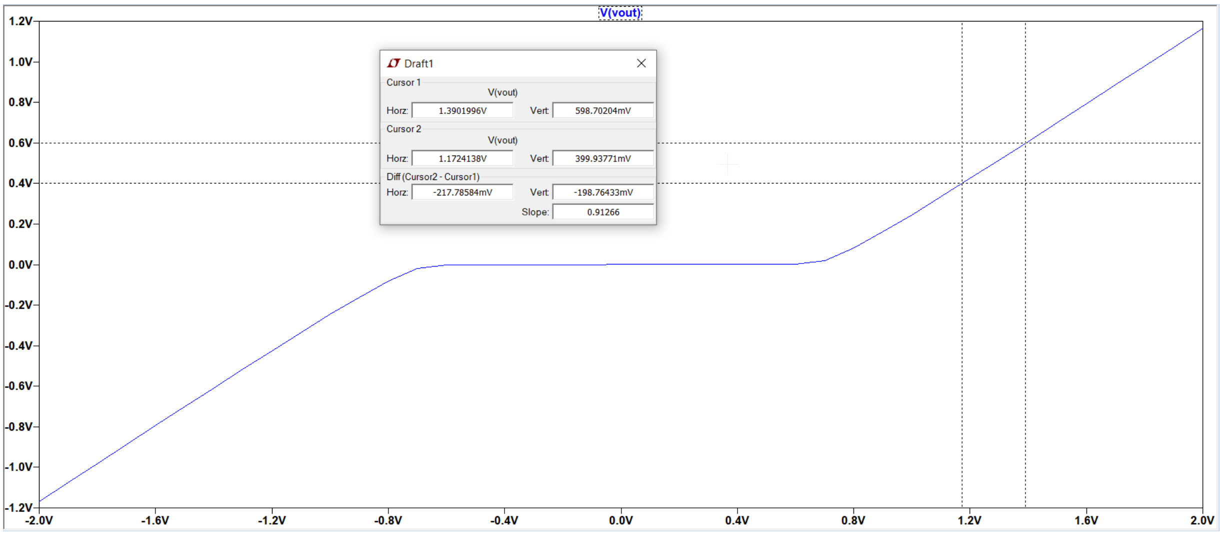
Good luck for the exam

QUESTION 4 (LT-SPICE)

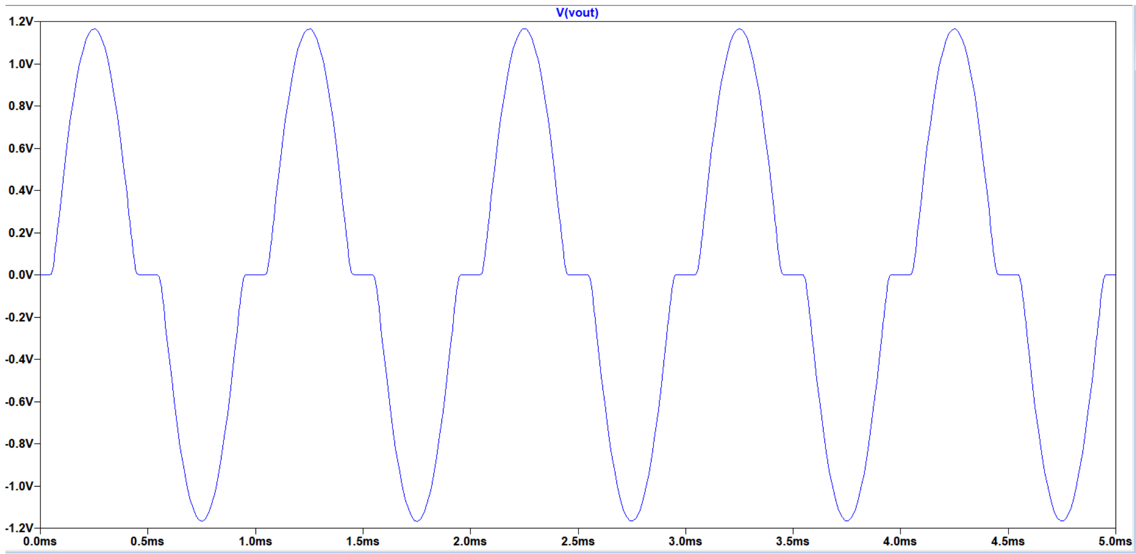
For the transfer characterisctic, you need to complete DC sweep simulation between -2V and 2V. You can see it below. The dead-zone is between -630 mV and 630 mV, which is an expected result. Please zoom to the plots.



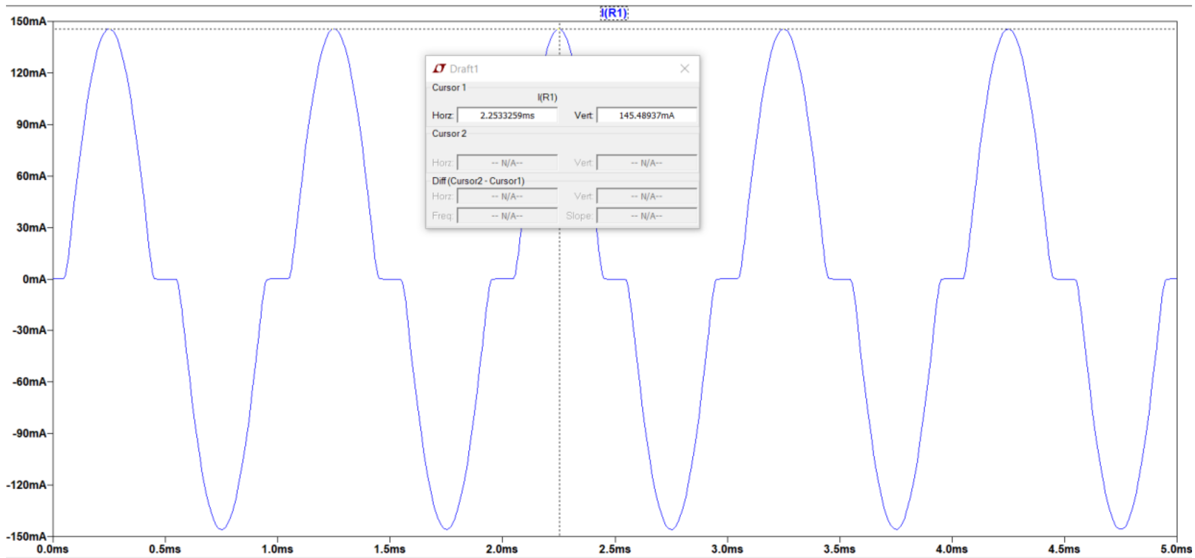
You can observe the slope for the gain, which is equal to 0.91 V/V as given below.

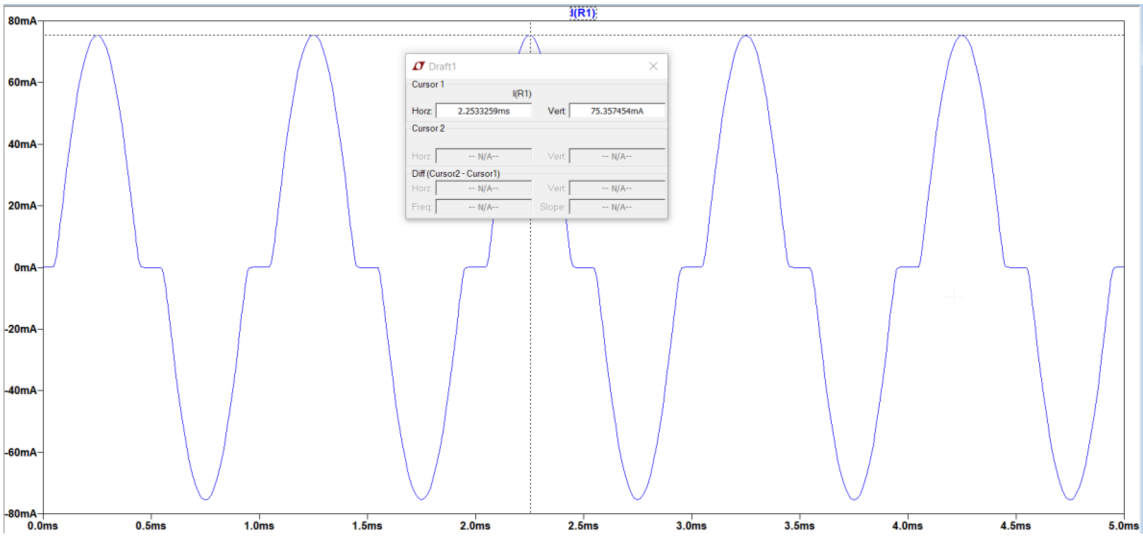


When you apply a sinusoidal signal with 2V peak voltage (you should choose a frequency) with 1 kHz (you can choose another appropriate frequency) you can observe the output and cross-over distortion, which is expected from a class B output stage.



For 16 ohm load resistance, you won't see any reasonable change in DC transfer characteristics and transient analysis. However, if you zoom to the maximum output levels, for 8 ohm it is around 1.16V whereas for 16 ohm it is around 1.2V. Let's plot the output current waveforms for 2 different load resistance value. The peak current for 8 ohm load is equal to 145 mA whereas it is equal to 75 mA for 16 ohm load. This is why the output voltage levels are different from each other. V_{BE} value of the transistors is depend on the current value!. You would observe more dramatic change if you increase the difference of the load resistors.





Important note: Observe the maximum output voltages. They are equal to ($2V-V_{Benpn}$) or ($-2V+|V_{BEpnp}|$) instead of 2V and -2V.