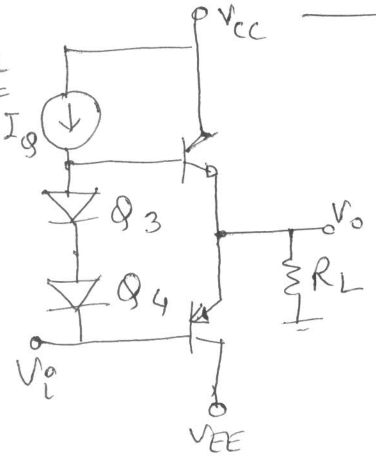
i.e., at $V_{ce_1} = $

$\therefore$ $V_{OM} = V_{CC} - V_{CE(sat)} = \underline{\underline{11.8\,V}}$ $\quad I_{supply} = \dfrac{V_{OM}}{\pi R_L} = \dfrac{11.8}{\pi \times 10^3} = \underline{\underline{3.756\,mA}}$

$P_{supply} = 2V_{CC}I_{supply} = 2 \times 12 \times 3.756 = \underline{\underline{90.15\,mW}}$ $\quad P_L = \dfrac{V_{OM}^2}{2R_L} = \dfrac{11.8^2}{2 \times 10^3} = \underline{\underline{69.62\,mW}}$

$\Rightarrow \eta = \dfrac{P_L}{P_{supply}} = \dfrac{69.62}{90.15} = \underline{\underline{77.23\%}}$. Max. Q_1/Q_2 dissipation occurs at middle of load line, i.e., at $V_{ce_1} = \dfrac{V_{CC}}{2} = \underline{\underline{6\,V}}$ & $I_{C_1} = \dfrac{V_{CC}}{2R_L} = \underline{\underline{6\,mA}}$, $\because$ each of Q_1 & Q_2 conducts for only 1/2 cycle $\Rightarrow P_{C_1 max} = P_{C_2 max} = \underline{\underline{36\,mW}}$.

2



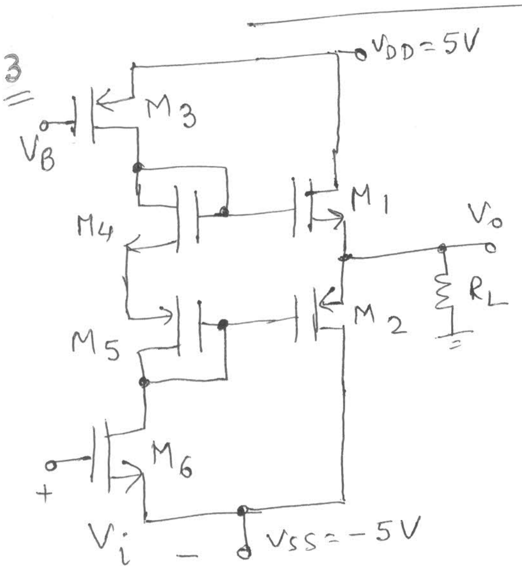
a) $V_o^- = V_{EE} + V_{EC_2}(sat) = \underline{-14.8\,V}$, & would remain independent of R_L. On the other hand, V_o^+ would depend on R_L, $\because$ with I_Q fixed at $200\,\mu A$, the max. current that Q_1 can deliver $= I_{C1,max} = (\beta_{npn}+1) I_Q = 201 \times 200\,\mu A = \underline{40.2\,mA}$. Thus, $V_o^+ = I_{C1,max} R_L$, provided that it is less than or equal to $[V_{CC} - V_{CE1}(sat)] = \underline{14.8\,V}$. For $R_L = 10\,k\Omega$, $I_{C1,max} R_L = 402\,V$, which is way higher than $14.8\,V \Rightarrow V_o^+ = \underline{14.8\,V}$ & the o/p would be symmetric. Similarly, for $R_L = 1\,k\Omega$, $I_{C1,max} R_L = 40.2\,V \Rightarrow V_o^+ = \underline{14.8\,V}$, & again the o/p would be symmetric. However, for $R_L = 200\,\Omega$, $I_{C1,max} R_L = 8.04\,V$, which is less than $14.8\,V \Rightarrow$ for this case, $V_o^+ = \underline{8.04\,V}$, & the o/p is asymmetric & highly distorted.

b) With $R_L = 1\,k\Omega$, $V_{om} = 14.8\,V \Rightarrow P_{L,max} = \frac{1}{2}\frac{V_{om}^2}{R_L} = \underline{109.52\,mW}$. Supply power $P_{supply} = \frac{2V_{CC}V_{om}}{\pi R_L} = \underline{141.33\,mW} \Rightarrow \eta = \frac{P_{L,max}}{P_{supply}} = \underline{0.775}\ (= \underline{77.5\%})$.

The mid-pt. of load line: $V_{ce} = \frac{V_{CC}}{2} = \underline{7.5\,V}$, & $I_c = \frac{V_{ce}}{R_L} = \underline{7.5\,mA} \Rightarrow$

$P_{C1,max} = P_{C2,max} = V_{ce} I_c = \underline{56.25\,mW}$

3



$I_{D6} = I_{D3} = I_{D4} = I_{D5} = 10\,\mu A$, & $\left(\frac{W}{L}\right)_3 = \left(\frac{W}{L}\right)_6 = 100$.

$I_{D3} = 10\,\mu A = \frac{k_p'}{2}\left(\frac{W}{L}\right)_3 (|V_{GS3}| - |V_{TP3}|)^2$

$= \frac{30\times10^{-6}}{2} \times 100 \times (|V_{GS3}| - 1)^2 \Rightarrow |V_{GS3}| = \underline{1.082\,V}$

$\Rightarrow V_{GS3} = -1.082\,V = V_B - V_{DD} \Rightarrow V_B = \underline{3.918\,V}$.

Also, $I_{D6} = 10\,\mu A = \frac{k_n'}{2}\left(\frac{W}{L}\right)_6 (V_{GS6} - V_{TN6})^2$

$= \frac{60\times10^{-6}}{2} \times 100 \times (V_{GS6} - 0.7)^2 \Rightarrow V_{GS6} = V_i = \underline{0.758\,V}$ (Quiescent Value)

Now, with $V_o = 3\,V$ & $R_L = 1\,k\Omega$, M_1 should be able to deliver $\frac{V_o}{R_L} = 3\,mA$ to the load, & under this Condn., M_3 should remain saturated. Min. reqd. $|V_{DS3}| = |V_{GS3}| - |V_{TP3}| = \underline{82\,mV}$. Note that it is slightly greater than the min allowed saturation voltage of $3V_T$, which is $78\,mV \Rightarrow$ should be okay. $\Rightarrow V_{G1} = V_{DD} - |V_{DS3}| = \underline{4.918\,V}$, & $V_{S1} = V_o = 3V \Rightarrow V_{GS1} = \underline{1.918\,V} \Rightarrow \left(\frac{W}{L}\right)_1 = \frac{2I_{D1}}{k_n'(V_{GS1} - V_{TN1})^2} = \frac{2\times3\times10^{-3}}{60\times10^{-6}\times(1.918-0.7)^2} = \boxed{67.41}$. Similarly, when $V_o = -3V$, M_2 should be able to sink $\underline{3\,mA}$. Under this condn., M_6 should remain saturated. Min. reqd. $V_{DS6} = V_{GS6} - V_{TN6} = \underline{58\,mV}$, which is lower than the smallest permissible value of $78\,mV$. $\therefore$ We should not let V_{DS6} fall below $78\,mV \Rightarrow V_{G2} = V_{SS} + V_{DS6} = \underline{-4.922\,V}$

Also, with $V_{S2} = V_O = -3V$, $V_{GS2} = \underline{-1.922V}$. $\therefore \left(\frac{W}{L}\right)_2 = \frac{2 I_{D2}}{K_p'(|V_{GS2}| - |V_{TP2}|)^2}$ (2)

$= \frac{2 \times 3 \times 10^{-3}}{30 \times 10^{-6} \times (1.922-1)^2} = \underline{235.27}$. For the calculation of aspect ratios of M_4

& M_5, consider idling cond^n, with $V_O = 0$, & idling current of $100\mu A$ flowing

thru $M_1 - M_2$. Thus, $I_{D1} = 100\mu A = \frac{K_n'}{2}\left(\frac{W}{L}\right)_1 (V_{GS1} - V_{TN1})^2 = \frac{60 \times 10^{-6}}{2} \times 67.41 \times$

$(V_{GS1} - 0.7)^2 \Rightarrow V_{GS1} = 0.922V \Rightarrow V_{G1} = V_{G4} = \underline{0.922V}$ ($\because V_{S1} = V_O = 0$).

Now, from the symmetry of the ckt., $\underline{V_{S4} = V_{S5} = 0}$, which gives $V_{GS4} = V_{G4} =$

$\underline{0.922V}$. Also, the idling current flowing thru M_1 should equal $10\mu A$. $\therefore$

$\left(\frac{W}{L}\right)_4 = \frac{2 I_{D4}}{K_n'(V_{GS4} - V_{TN4})^2} = \frac{2 \times 10 \times 10^{-6}}{60 \times 10^{-6} \times (0.922-0.7)^2} = \underline{6.76}$ (note how small

this is as compared to $(W/L)_1$). Similarly, for M_2, we get $I_{D2} = 100\mu A =$

$\frac{K_p'}{2}\left(\frac{W}{L}\right)_2 (|V_{GS2}| - |V_{TP2}|)^2 = \frac{30 \times 10^{-6}}{2} \times 235.27 \times (|V_{GS2}| - 1)^2 \Rightarrow |V_{GS2}| = \underline{1.168V}$

$\Rightarrow V_{G2} = V_{G5} = \underline{-1.168V}$ ($\because V_{S2} = V_O = 0$) $\Rightarrow$ Also, $\because V_{S5} = 0$, $\therefore V_{GS5} = \underline{-1.168V}$.

$\therefore \left(\frac{W}{L}\right)_5 = \frac{2 I_{D5}}{K_p'(|V_{GS5}| - |V_{TP5}|)^2} = \frac{2 \times 10 \times 10^{-6}}{30 \times 10^{-6} \times (1.168-1)^2} = \underline{23.62}$ (note how small

it is as compared to $\left(\frac{W}{L}\right)_2$). This completes the design.

* The ratio of the aspect ratio of the o/p transistor & pre-bias transistor

is equal to the ratio of the idling current. * $\because M_1 - M_2$ branch carries an

idle current of $100\mu A$, & $M_4 - M_5$ branch carries an idling current of $10\mu A$,

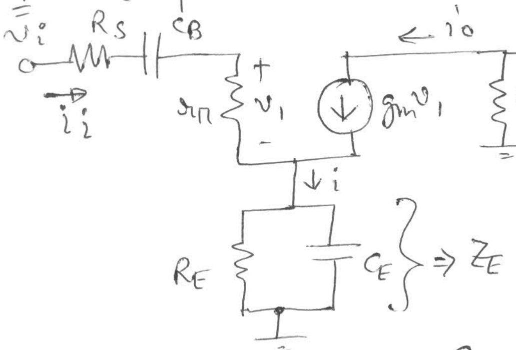
$\therefore$ the aspect ratio of M_1 (M_2) should be ~ 10 times that of M_4 (M_5), which

we have rigorously proved in this problem, i.e., $\frac{(W/L)_1}{(W/L)_4} = \frac{67.41}{6.76} = \underline{9.97}$, &

$\frac{(W/L)_2}{(W/L)_5} = \frac{235.27}{23.62} = \underline{9.96}$ [Note how close these values are to 10]

$\times$ ... $\sim \beta \beta I_D R_L = 150 \times 150 \times 150\mu A \times 1k\Omega =$

4 The eqv. ckt.



$Z_E = R_E \| \frac{1}{sC_E} = \frac{R_E}{1+sR_EC_E}$, $v_o = -i_o R_C = -g_m R_C v_1$, $v_1 = i_i r_\pi$, $i = i_o + i_i = (1+g_m r_\pi)\, i_i$, and $i_i = \frac{v_i - iZ_E}{R_S + \frac{1}{sC_B} + r_\pi}$

$$\Rightarrow v_i = i_i\left[\frac{s(R_S+r_\pi)C_B+1}{sC_B}\right] + i\,\frac{R_E}{1+sR_EC_E}$$

$$\Rightarrow v_i = i_i\left[\frac{(1+sR_EC_E)[s(R_S+r_\pi)C_B+1]+s(1+\beta)R_EC_B}{sC_B(1+sR_EC_E)}\right] \quad (\because g_m r_\pi = \beta)$$

$$\text{Now, } v_1 = i_i r_\pi = v_i\,\frac{s r_\pi C_B(1+sR_EC_E)}{s(R_S+r_\pi)C_B+1+s^2R_E(R_S+r_\pi)C_BC_E+sR_EC_E+s(1+\beta)R_EC_B}$$

$$\Rightarrow v_o = -g_mR_Cv_1 = -g_mR_C\,\frac{s r_\pi C_B(1+sR_EC_E)}{1+s[R_EC_E+\{R_S+r_\pi+(1+\beta)R_E\}C_B]+s^2R_E(R_S+r_\pi)C_BC_E}\,v_i$$

$$\Rightarrow A_v(s) = \frac{v_o}{v_i}(s) = A_{vo}\,\frac{(s/\omega_B)(1+s/z_1)}{1+a_1s+a_2s^2}$$ (Look at the complexity of solⁿ.)

where $A_{vo} = -g_mR_C$, $\omega_B = \frac{1}{r_\pi C_B}$, $z_1 = \frac{1}{R_EC_E}$, $a_1 = [R_EC_E + \{R_S + r_\pi + (1+\beta)R_E\}C_B]$, and $a_2 = R_E(R_S+r_\pi)C_BC_E$. Thus, the low freq. response has a zero at zero freq., another −ve real zero at z_1, & 2 −ve real poles, which can be evaluated by solving the quadratic expression in the denominator. Thus, the actual freq. resp. characteristic is pretty complicated. Now, $I_C = 1$ mA $\Rightarrow r_E = 26\,\Omega$, & $r_\pi = 5.2\,k\Omega$ ($\beta = 200$). $\omega_B = \frac{1}{r_\pi C_B} = 19.23$ rad/sec $\Rightarrow f_B = \omega_B/(2\pi) = \boxed{3.06\text{ Hz}}$, $z_1 = \frac{1}{R_EC_E} = 20$ rad/sec $\Rightarrow f_{z_1} = \boxed{3.18\text{ Hz}}$. The coeffs. $a_1 = R_EC_E + [R_S + r_\pi + (\beta+1)R_E]C_B = 1.117$, & $a_2 = R_EC_E(R_S+r_\pi)C_B = 3.1\times10^{-3}$ $\Rightarrow D(s) = 1 + 1.117s + 3.1\times10^{-3}s^2$, with solⁿ.s 2 −ve real roots at -0.898 & -359.42 $\Rightarrow \omega_{P_1} = 0.898$ rad/sec & $\omega_{P_2} = 359.42$ rad/sec $\Rightarrow f_{P_1} = \boxed{0.14\text{ Hz}}$ & $f_{P_2} = \boxed{57.2\text{ Hz}}$. Thus, the actual lower cutoff freq. is at 57.2 Hz (the highest of all poles & zeros). Now, using the IVTC technique, $R_B^\infty = R_S + r_\pi = 6.2\,k\Omega$ $\Rightarrow \tau_1 = R_B^\infty C_B = 62$ mS $\Rightarrow f_1 = \frac{1}{2\pi\tau_1} = 2.57$ Hz, and $R_E^\infty = R_E \| \left[r_E + \frac{R_S}{\beta+1}\right] = 29.17\,\Omega$ $\Rightarrow \tau_2 = R_E^\infty C_E = 2.917$ mS $\Rightarrow f_2 = \frac{1}{2\pi\tau_2} = 54.56$ Hz $\Rightarrow f_L = \sqrt{f_1^2+f_2^2} = 54.62$ Hz (compare with 57.2 Hz obtd. from the exact analysis, & appreciate the simplicity of IVTC.

5 Refer to P8 (HA#8). The bias pt. has already been calculated, & $r_{E1} = r_{E2} = r_E = \underline{24.76\,\Omega}$, $r_\pi = \underline{2.48\,k\Omega}$, & $R = R_1 \| R_2 = \underline{31.97\,k\Omega}$. ∵ There are 5 caps. in the ckt., we will have five time consts., & five cutoff freqs.

For C_1, $R_1^\infty = R_S + R \| r_\pi = \underline{7.3\,k\Omega} \Rightarrow \tau_1 = R_1^\infty C_1 = \underline{73\,ms} \Rightarrow f_1 = \frac{1}{2\pi\tau_1} = \underline{2.18\,Hz}$.

For C_2, $R_2^\infty = R_{E_1} \| \left[r_E + \frac{R_S \| R}{\beta+1}\right] = \underline{66.42\,\Omega} \Rightarrow \tau_2 = R_2^\infty C_2 = \underline{6.64\,ms} \Rightarrow f_2 = \underline{23.96\,Hz}$

For C_3, $R_3^\infty = R_{C_1} + R \| r_\pi = \underline{9.1\,k\Omega} \Rightarrow \tau_3 = R_3^\infty C_3 = \underline{91\,ms} \Rightarrow f_3 = \underline{1.75\,Hz}$.

For C_4, $R_4^\infty = R_{E_2} \| \left[r_E + \frac{R_{C_1} \| R}{\beta+1}\right] = \underline{78.66\,\Omega} \Rightarrow \tau_4 = \underline{7.87\,ms} \Rightarrow f_4 = \underline{20.23\,Hz}$.

For C_5, $R_5^\infty = R_{C_2} + R_L = \underline{8.8\,k\Omega} \Rightarrow \tau_5 = \underline{176\,ms} \Rightarrow f_5 = \underline{0.9\,Hz}$

$\therefore f_L = \left[\sum_{i=1}^{5} f_i^2\right]^{1/2} = \boxed{31.5\,Hz}$ → Overall lower cutoff freq. of the amplifier.

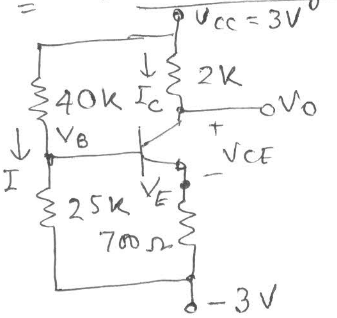
$P \leq 10\%$ $\left(= \frac{\pi f_L}{f} \times 100\%\right) \Rightarrow f = \frac{\pi f_L}{P} \times 100 = \underline{989.6\,Hz}$ → min freq. for ≤10% tilt

---

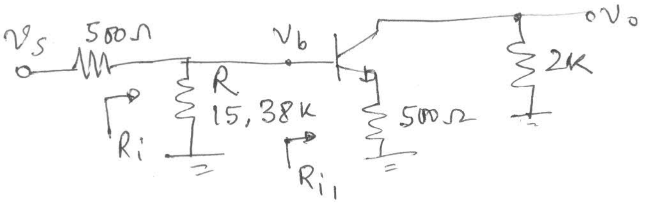
6 a) DC Analysis: All capacitors open up. Neglecting base current, $I = \frac{6}{40+25} = \underline{92.31\,\mu A} \Rightarrow V_B = -3 + 92.31\,\mu A \times 25K = \underline{-0.692V}$

$\Rightarrow V_E = V_B - V_{BE} = \underline{-1.392V} \Rightarrow I_C \simeq I_E = \frac{-1.392+3}{700} = \underline{2.3\,mA}$

& $V_o = V_{CC} - I_C \times 2K = 3 - 2.3\,mA \times 2k = \underline{-1.6\,V}$



b) For ac analysis, at midband, all caps. short out, thus shunting 200Ω resistor at the emitter lead.



$R = 40K \| 25K = \underline{15.38K}$

$r_E = \frac{V_T}{I_C} = 11.3\,\Omega$, $r_\pi = \beta r_E = \underline{2.26K}$

$R_{i_1} = r_\pi + (\beta+1) \times 500 = \underline{102.76K}$

$R_i = R \| R_{i_1} = \underline{13.38K}$

$\frac{v_o}{v_b} = -\frac{2K}{11.3+500} = \underline{-3.9}$, $\frac{v_b}{v_s} = \frac{R_i}{R_i + 500} = \underline{0.96} \Rightarrow \frac{v_o}{v_s} = \frac{v_o}{v_b} \times \frac{v_b}{v_s} = \underline{-3.76}$

c) C_E made arbitrarily large ⇒ 200Ω resistor remains shorted out.

$R_B^\infty = 500 + R_i = \underline{13.88k}$. ∵ f_L is 20 Hz, ∴ $C_B = \frac{1}{2\pi f_L R_B^\infty} = \underline{0.57\,\mu F}$

d) C_B is made arbitrarily large. For this case, $R_E^\infty = 200\,\Omega \| R^*$, where

$R^* = 500 + r_E + \frac{15.38K \| 500K}{201} = \underline{513.7\,\Omega} \Rightarrow R_E^\infty = \underline{143.95\,\Omega}$. ∴ for $f_L = 20\,Hz$,

$C_E = \frac{1}{2\pi f_L R_E^\infty} = \underline{55.28\,\mu F}$

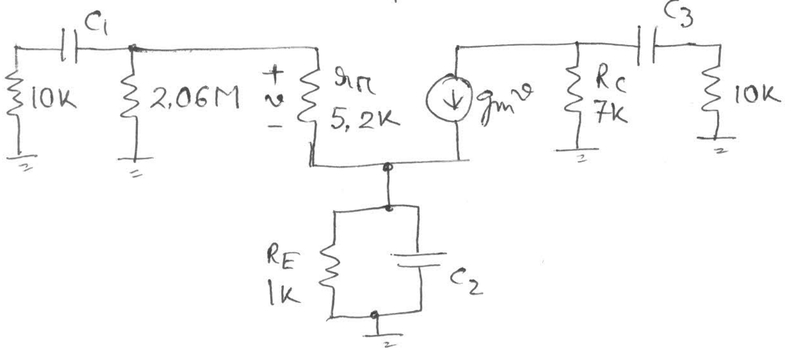
e) ∵ C_E "sees" much lower resistance than C_B, ∴ we choose C_E to contribute the dominant pole, f_d. ∴ The pole contributed by C_B will be at $f_d/10$, such that $\sqrt{f_d^2 + (f_d/10)^2} = 20 = f_L \Rightarrow f_d = \underline{19.9\,Hz}$ & $f_d/10 = \underline{1.99\,Hz}$.

$\Rightarrow C_B = \frac{1}{2\pi (f_d/10) R_B^\infty} = \underline{5.76\,\mu F}$, & $C_E = \frac{1}{2\pi f_d R_E^\infty} = \underline{55.56\,\mu F}$

$\Rightarrow \Sigma C = \underline{61.32\,\mu F}$ ⇒ which is the minimum possible, given the design paradigm.

---

7 From Prob. 5 (HA # 8), $R_C = 7K\Omega$ & $R_B = 2.06\,M\Omega$. The i/p is being a current source, we open it. The small signal equ. can be drawn as: (5)



For C_1, $R_1^\infty = 10K + 2.06M \| 5.2K = 15.2K$

For C_2, $R_2^\infty = 1K \| \left(\dfrac{5.2K + 2.06M\|10K}{201}\right)$

$= 70.1\,\Omega$

For C_3, $R_3^\infty = 10K + 7K = 17K$

R_2^∞ is least $\Rightarrow$ pick C_2 to contribute the dominant pole f_d. C_1 & C_3 contribute poles at $f_d/10$ each.

$\Rightarrow \sqrt{f_d^2 + 2(f_d/10)^2} = f_L = 20\,Hz \Rightarrow f_d = 19.8\,Hz$ $\quad f_d/10 = 1.98\,Hz$

$\Rightarrow C_2 = \dfrac{1}{2\pi f_d R_2^\infty} = 114.7\,\mu F$, $\quad C_1 = \dfrac{1}{2\pi (f_d/10) R_1^\infty} = 5.3\,\mu F$, &

$C_3 = \dfrac{1}{2\pi (f_d/10) R_3^\infty} = 4.73\,\mu F \Rightarrow \Sigma C = 124.73\,\mu F$

b) $P = \dfrac{\pi f_L}{f} \times 100\% = \dfrac{\pi \times 20}{200} \times 100 = 31.4\%$

c) $P = 2\% \Rightarrow f = \dfrac{\pi f_L}{P} \times 100 = \dfrac{\pi \times 20}{2} \times 100 = 3.14\,KHz$