1. (40 points) Determine the low-frequency response for the ER amplifier to the right when $C_C = 4\mu F$, $C_B = 2\mu F$, $R_1 = 10k\Omega$, $R_2 = 90k\Omega$, $R_C = 1k\Omega$, $R_E = 200\Omega$, $R_L = 2k\Omega$, $\beta = 100$, $V_{BE} = 0.7V$, $V_{CC} = 20V$, and $R_S << R_{in}$. 

Extra Credit (20 points max): Sketch the straight line approximations for the gain and phase Bode plots and provide values for actual plots.

2. (30 points) Consider an inverting amplifier with an ideal gain of 1000 V/V constructed from an op amp with an input offset voltage of 3 mV and with output saturation levels of $\pm 10V$. 

Hint: Assume $R_F >> R_o$ and that $G_o$, $R_{cm}$ and $R_i$ are much larger than either $R_A$ or $R_F$. 

a. What is (approximately) the peak sine-wave input signal that can be applied without the output clipping?

b. If the effect of $V_{io}$ is nulled at room temperature (25°C) how large an input may be applied if:

i. the circuit is to operate at a constant temperature of 25°C?

ii. the circuit is to operate at a temperature in the range 0°C to 75°C and the temperature coefficient of $V_{io}$ is $10\mu V/°C$?

3. (30 points) Design a single 741 op-amp that will generate $v_{out} = 3v_1 + 5v_2 - 8v_3 - 6v_4$, when the equivalent resistance at the negative and positive terminals is $R_{eq} = 8k\Omega$. Determine each resistor value, input resistance at each of the amplifier inputs and the output resistance. Draw the schematic and show the resistor values.

Extra Credit (Maximum 15 points) Design an emitter-resistor circuit as shown in Problem 1 with $V_{CC} = 12V$, $\beta = 250$, $R_L = 1k\Omega$, $R_S = 2k\Omega$ and $A_V = -5$ V/V. Select $C_B$ and $C_C$ so that the amplifier has a lower 3dB frequency of 20Hz. $I_C$ is to be in the middle of the ac load line.
Given: $C_c = 4 \mu F$

- $C_B = 2 \mu F$
- $R_1 = 10 \, k\Omega$
- $R_2 = 90 \, k\Omega$
- $R_C = 1 \, k\Omega$
- $R_E = 200 \, \Omega$ \quad $0.2 \, k\Omega$
- $R_L = 2 \, k\Omega$
- $\beta = 100$
- $V_{BE} = 0.7 \, V$
- $V_{CC} = 20 \, V$
- $R_S << R_{in}$

$R_C << R_{in} \Rightarrow V_{in} \approx V_S$

$R_E = R_1 \parallel R_2 = 10k \parallel 90k = 9k \Omega$

$V_{BE} = \frac{R_1 \cdot V_{CC}}{R_1 + R_2} = \frac{(10k)(20)}{10k + 90k} = 2 \, V$

$I_C = \frac{V_{BE} - V_{BE}}{R_E + \beta + R_E} = \frac{2 - 0.7}{100 + 0.2k} = 4.49 \, mA$

$r_e = \frac{V_I}{I_C} = \frac{26mV}{4.49mA} = 5.8 \, \Omega$ \quad $r_{t} = 580 \, \Omega$

$Av_{small} = -\frac{r_L}{r_C} = \frac{-2k}{1k} = -3.24 \, V/V$

$C_c \text{ short, } R_{CB} = R_S + R_{E} \left( \frac{r_t + \beta \cdot r_E}{R_{in} + \beta \cdot r_E} \right)$

$C_c \text{ short, } R_{C} = R_{C} + R_L$
\[ T_{cb} = C_{cb} R_{ce} = (24) \left[ 9K \ 11 \ (580+20K) \right] = (24) \left[ 9K \ 11 \ 20.58k \right] \]

\[ T_{cb} = 12.5 \text{ms} \quad \Rightarrow \quad \omega_{ce} = \frac{1}{T_{cb}} \approx 80 \text{rad/s} \quad f_{cb} \approx 12.73 \text{Hz} \]

\[ T_{ce} = C_{c} R_{ce} = \left( \frac{1}{4} \right) (3K) = 12 \text{mS} \quad \Rightarrow \quad \omega_{ce} = 83.3 \text{rad/s} \quad f_{ce} \approx 13.26 \text{Hz} \]

\[ \omega_{L} \approx \frac{1}{T_{cb}} + \frac{1}{T_{ce}} = \frac{1}{12.5 \text{mS}} + \frac{1}{12 \text{mS}} \approx 163.3 \text{ rad/s} \]

\[ f_{L} \approx \frac{\omega_{L}}{2\pi} = 26 \text{ Hz} \]

**Note**

Better approx from

\[ f_{L} = \sqrt{f_{cb}^2 + f_{ce}^2} = \sqrt{(12.73)^2 + (13.26)^2} \approx 18.4 \text{ Hz} \]

Form of transfer function

\[
\frac{A_V(s)}{A_{in} \text{band}} = \frac{s^2}{(s+\omega_{cb})(s+\omega_{ce})} = \frac{s^2}{(s+80)(s+83.3)}
\]

double zero at zero

pole at \( \omega = 80 \text{ rad/sec} \)

pole at \( \omega = 83.3 \text{ rad/sec} \)

straight line slope 5db/decade

+40 db/decade, \( \omega < 80 \text{ rad/sec} \)

+20 db/decade, \( 80 \leq \omega \leq 83.3 \text{ rad/sec} \)

0db/decade, \( \omega \geq 83.3 \text{ rad/sec} \)

\( \omega \) rad

+180 from double zero

-45° at \( \omega = 80 \)

-45° at \( \omega = 83.3 \)
\[ A_v = A_v(j\omega) = \frac{(j\omega)^2}{A_{mid}(j\omega+80)(j\omega+83.3)} \]

\[ |A_v| = \frac{\omega^2}{\sqrt{(\omega^2+80^2)(\omega^2+83.3^2)}} \]

| \omega | |A_v| | |\omega| |dB|
|---|---|---|---|---|
| 1  | 1.5x10^{-4} | -76.5 | 778.59 |
| 10 | 1.48x10^{-2} | -36.6 | 146.02 |
| 80 | 0.49 | -6.2 | 91.16 |
| 83.3 | 0.51 | -5.8 | 88.84 |
| 100 | 0.6 | -4.4 | 78.45 |
| 800 | 0.99 | -0.09 | 11.65 |
| 833 | 0.99 | -0.07 | 11.2 |
| 1000 | 0.993 | -0.05 | 9.33 |
3. **Assumptions:**

- $A_v = \frac{-RF}{RA} = -1000 \text{ V/V}$
- Output dc offset voltage: $V_o = |A_v| \cdot V_{io}$

\[ V_o = (3 \text{ mV})(1000) = 3 \text{ V} \]

**: The maximum signal at the output is**

\[ 10 - 3 = 7 \text{ V (before saturation)} \]

The max input signal, $V_{in} = \frac{7}{|A_v|} = 7 \text{ mV}$

b) If $V_{io}$ nulled (cancelled) @ $25^\circ C$

i) @ $25^\circ C$ (constant): $V_{in} = \frac{V_{max}}{|A_v|} = \frac{10}{1000} = 10 \text{ mV}$

ii) $\frac{\Delta V_{io}}{V_{io}(T)} = 10 \text{ mV/}^\circ C$, need max change with respect to nominal temperature of $25^\circ C$ ⇒ worst case

- @ $T = 0^\circ C$, $\Delta T = 25 - 0 = 25^\circ C$
- @ $T = 75^\circ C$, $\Delta T = 75 - 25 = 50^\circ C$ (worst case)

$\Delta V_{io} = (\frac{10 \text{ mV}}{\circ C})(50^\circ C) = 500 \text{ mV} = 0.5 \text{ V}$

**: max allowable output (before saturation) is**

\[ 10 - 0.5 = 9.5 \text{ V} \]

\[ \frac{V_{in}(\text{max})}{1000} = 9.5 \text{ mV} \]
$v_0 = 3v_1 + 5v_2 - 8v_3 - 6v_4$

$R_{eq} = 8k\Omega$

**Generic op-amp:**

Rewrite: $v_0 = 3v_1 + 5v_2 - 8v_3 - 6v_4$

have 2 non-inv inputs

$X = \sum X_i$ (non-inv), $Y = \sum Y_j$ (inv), $Z = X - (Y+1)$

$x_1 = 3, x_2 = 5, y_1 = 8, y_2 = 6$

$x = 8, y = 14, Z = -7$

Case II: $Z < 0, R_y \to \infty, R_x = \frac{RF}{2}, R_i = RF/x_i, R_j = RF/y_j$

choose $RF = (Y+1)/15, R_{eq} = (15)(8k) = 120k\Omega$

$R_x = 17.1k\Omega$

$R_y = 15k\Omega$

$R_1 = 40k\Omega$

$R_2 = 24k\Omega$

$R_{in1} = R_1 + (R_2 || R_x) = 50k\Omega$

$R_{in2} = R_2 + (R_1 || R_x) = 36k\Omega$

$R_{in1} = 15k\Omega$

$R_{in2} = 20k\Omega$

$R_0 = \frac{R_0}{G_0} (Y+1) = \frac{(75)(15)}{10^3} \approx 11.3\text{m\Omega}$
Let \( R_c = R_L = 1k \Omega \)  
\( R_{ac} = R_c \{ R_L + R_e \} \)  
\( R_{dc} = R_c + R_e \)

**ER:**  
\( A_v = \frac{-R_{ac}}{R_{dc}} \)  
Assume \( R_e >> R_c \)

\[-5 = \frac{(1k \text{ in } 1k)}{R_e} \]  
\( R_e = \frac{500}{5} = 100 \Omega \)

\[ I_{Cq} = \frac{V_{cc}}{R_{ac} + R_{dc}} = \frac{12}{100 + 1100} = 0.0106 \text{mA} \]  
\( r_c = \frac{V_T}{I_{Cq}} = \frac{26m}{7.2m} = 3.65 \Omega \)

Assumption \( q_2 \) (most of \( R_e \) is \( 96 \Omega \))

\( R_B = 0.1 \beta R_e = (0.1)(250)(100) = 2.5k \Omega \)

\( V_{BE} = V_{BE} + I_{Cq}(\frac{R_B + R_e}{1.1R_e}) = 1.48V \)

\[ R_1 = \frac{R_B V_{cc}}{V_{cc} - V_{BE}} = \frac{(2.5K)(12)}{12 - 1.48} = 28.5K \Omega \]  
\( R_2 = \frac{R_A V_{cc}}{V_{BE}} = \frac{7.8K}{1.48} = 5.27K \Omega \)

\[ R_{in} = R_B \beta (r_c + R_e) = 2.27K \Omega \]

\[ R_{CE} = R_c + R_L = 2K \Omega \]  
\( R_{CB} = R_s + R_{in} = 4.27 \Omega \)

Set breaks 1 decade apart and use output for \( f_2 \)

**Small signal resistance**

\[ C_C = \frac{1}{2\pi f_L R_C} = \frac{1}{2\pi (20)(2K)} = 3.98 \mu F \]

\[ C_B = \frac{1}{2\pi f_L R_{CB}} = \frac{1}{2\pi (2)(4.27K)} = 18.6 \mu F \]