1) The incremental equivalent circuit for an amplifier is shown. Select a value for \( C_E \) to obtain a 3db low-frequency roll-off at 1 kHz (nominal). Compare the specified and the computed response.

**Answer**

\[
G_{MB} = \frac{1}{2+6} \cdot \frac{6}{4+6+4} (-99)(3.3) = -470 \text{ (53.5 dB)}
\]

\[
T_I = (0.1)(2+6||4) = 0.44 \text{ msec}
\]

\[
T_E = \frac{C_E}{100} \cdot 0.05 \cdot (100) \cdot (4+6||2) = 0.026 C_E \text{ msec}
\]

\[
2\pi = \frac{1}{0.44} + \frac{1}{0.026 C_E}
\]

\[
C_E = 9.6 \mu F; \text{ use } 10 \mu F
\]

---

**PROBLEMS (low-frequency)**

---

**Problem 1**

VS 1 0 AC 1
RS 1 2 2K
CI 2 3 0.1U
RB 3 0 6K
RBE 3 4 4K
RE 4 0 50
CE 4 0 \( \{CVAL\} \)

.PARAM CVAL = 10U
.STEP PARAM CVAL LIST 5U 10U 15U
G1 5 4 3 4 0.247
RL 5 0 3.3K
.LIB EVAL.LIB
.AC DEC 20 100 100K
.PROBE
.END

---

**Graph**

A graph showing the frequency response of the amplifier with different values of \( C_E \) (5U, 10U, 15U) is included. The graph displays the voltage magnitude (\( V_{db}\)) against frequency (in Hz) from 100Hz to 100KHz.
2) The NPN amplifier stage involves only partial bypassing of the emitter feedback resistor. Specify CE for a 3db frequency of 0.5 kHz. Use PSpice to compute the rolloff and compare the computed frequency to the estimated value.

**Answer**

Determine the quiescent current, and from this the incremental parameter rbe:

\[ V_{thev} = 1.65 \text{V} \quad R_{thev} = 8.91 K\Omega \quad I_E = 1.49 \text{mA} \quad r_{be} = 2.11 K\Omega \]

Note the modified emitter feedback with partial bypassing, i.e., a residual feedback less than that for the DC operation is retained to stabilize AC operation. For simplicity in calculating the CE time constant transform the emitter impedance \( Z \) into the equivalent base impedance \( \beta + 1 \) \( Z \). This corresponds as before to multiplying all impedances by \( \beta + 1 \).

\[ Ti = (0.1)(1 + (8.91) + (2.11 + (0.22)(121))) = 0.78 \text{ msec} \]

\[ To = (0.1)(5.6 + 2.2) = 0.78 \text{ msec} \]

\[ \tau_E = \frac{CE}{121} \left[ (0.33)(121) \right] \left[ (0.22)(121) + 2.11 + (8.91)(1) \right] \]

\[ \tau = \frac{1}{0.78} + \frac{1}{0.78} + \frac{1}{0.14CE} \]

\[ CE \approx 1 \mu F \]

Calculate the mid-band voltage gain to be

\[ G_{MB}^W = \frac{1}{\frac{8.91}{1+8.91\left[ 2.11 + (0.22)(121) \right]}} \left[ \frac{(-120)(5.6)\left[ 2.2 \right]}{8.91 + 2.11 + (0.22)(121)\left[ 2.2 \right]} \right] \]

\[ = -5.75 \text{ (15.2db)} \]

**Problem 2**

<table>
<thead>
<tr>
<th>VS</th>
<th>RS</th>
<th>CI</th>
<th>RB1</th>
<th>RB2</th>
<th>Q1</th>
<th>RC</th>
<th>RE1</th>
<th>RE2</th>
<th>CE</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>2</td>
<td>4</td>
<td>3</td>
<td>5</td>
<td>4</td>
<td>7</td>
<td>8</td>
<td>8</td>
</tr>
<tr>
<td>0</td>
<td>2</td>
<td>3</td>
<td>3</td>
<td>0</td>
<td>3</td>
<td>5</td>
<td>8</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>AC</td>
<td>1K</td>
<td>0.1U</td>
<td>82K</td>
<td>10K</td>
<td>Q2N3904</td>
<td>5.6K</td>
<td>220</td>
<td>330</td>
<td>{CVAL}</td>
</tr>
<tr>
<td>1</td>
<td>1K</td>
<td>0.1U</td>
<td>82K</td>
<td>10K</td>
<td>Q2N3904</td>
<td>5.6K</td>
<td>220</td>
<td>330</td>
<td>{CVAL}</td>
</tr>
</tbody>
</table>

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The University of Michigan-Dearborn

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Computed bias point parameters are:

<table>
<thead>
<tr>
<th>NAME</th>
<th>Q1</th>
</tr>
</thead>
<tbody>
<tr>
<td>MODEL</td>
<td>Q2N3904</td>
</tr>
<tr>
<td>IC</td>
<td>1.56E-03</td>
</tr>
<tr>
<td>VBE</td>
<td>6.76E-01</td>
</tr>
<tr>
<td>VCE</td>
<td>5.43E+00</td>
</tr>
</tbody>
</table>

and the computed frequency response is:

3) Select values for $C_E$ and $C_i$ to obtain a 3db low-frequency roll-off at 1 kHz (nominal). Compare with the computed response. Suppose the value specified for $C_i$ is halved; specify a revised value for $C_E$ to maintain the (nominal) roll-off.

**Answer**

This is a PNP version of the preceding problem. The DC calculations to determine the operating point, and so $r_{be}$:

\[
VB = \frac{68}{53+68} \times 10 = 6.73\text{V}
\]

\[
RB=\frac{33}{68} = 22.2\text{K}\Omega
\]

\[
IE = \frac{10-6.73-0.7}{1.8+0.47+22.2} = 1.05\text{mA}
\]

\[
r_{be} = 3\text{K}\Omega
\]

The incremental parameter circuit is drawn to the right.
If $C_i$ is halved its contribution to the sum is doubled, and so because equal contributions (approximately) are used the contribution of $C_E$ should be halved, i.e., double the capacitance. Hence use $C_i = 0.01 \mu F$ and $C_E = 1 \mu F$.  

\[ G_{MB}^w = \frac{1}{1 + 22.2 || (3 + (1.21)(0.47)) || 22.2 + 3 + (1.21)(0.47) || (-120)(2.5) \} \]

\[ T_1 = C_i [1 + 22.2 || (3 + (0.47)(1.21)) || 17.2 \text{Ci msec} \]

\[ T_E = \frac{C_E}{121} \left\{ (1.8)(1.21) || (0.47)(1.21) + 3 + 22.2 || 1 \right\} \]

\[ \omega_{3\text{db}} = \frac{1}{2\pi} \frac{1}{17.2C_i} + \frac{1}{0.39C_E} \]

A convenient initial choice of values is one that assigns an equal contribution to the sum from each term: $C_i = 18.5 \text{nF} = 0.02 \mu F$, and $C_E = 0.82 \mu F = 0.5 \mu F$. 

Problem 3

<table>
<thead>
<tr>
<th>VS</th>
<th>1</th>
<th>0</th>
<th>AC</th>
<th>1</th>
<th>RE2</th>
<th>4</th>
<th>5</th>
<th>1.8K</th>
</tr>
</thead>
<tbody>
<tr>
<td>RS</td>
<td>1</td>
<td>2</td>
<td>1K</td>
<td></td>
<td>CE</td>
<td>5</td>
<td>0</td>
<td>0.5U</td>
</tr>
<tr>
<td>CI</td>
<td>2</td>
<td>3</td>
<td>0.02U</td>
<td></td>
<td>VCC</td>
<td>4</td>
<td>0</td>
<td>DC 10</td>
</tr>
<tr>
<td>RB1</td>
<td>4</td>
<td>3</td>
<td>33K</td>
<td></td>
<td>.LIB</td>
<td>EVAL.LIB</td>
<td></td>
<td></td>
</tr>
<tr>
<td>RB2</td>
<td>3</td>
<td>0</td>
<td>68K</td>
<td></td>
<td>.OP</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Q1</td>
<td>7</td>
<td>3</td>
<td>6</td>
<td>Q2N3906</td>
<td>.AC</td>
<td>DEC 20</td>
<td>100</td>
<td>100K</td>
</tr>
<tr>
<td>RC</td>
<td>7</td>
<td>0</td>
<td>2.5K</td>
<td></td>
<td>.PROBE</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>RE1</td>
<td>5</td>
<td>6</td>
<td>470</td>
<td></td>
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<td></td>
<td></td>
</tr>
</tbody>
</table>

Computed bias point parameters are:

<table>
<thead>
<tr>
<th>NAME</th>
<th>Q1</th>
<th>Q2N3906</th>
</tr>
</thead>
<tbody>
<tr>
<td>MODEL</td>
<td></td>
<td></td>
</tr>
<tr>
<td>IC</td>
<td>-1.08E-03</td>
<td></td>
</tr>
<tr>
<td>VBE</td>
<td>-7.03E-01</td>
<td></td>
</tr>
<tr>
<td>VCE</td>
<td>-4.85E+00</td>
<td></td>
</tr>
</tbody>
</table>

and the computed frequency response is:
4) Select values for $C_E$ and $C_i$ to obtain a 3db low-frequency roll-off at 1 kHz (nominal). Compare with the computed response.

**Answer** The Thevenin biasing resistance is $33||100 = 24.81\, \text{K}\Omega$, and the Thevenin voltage is 2.48 volts. The estimated emitter current is 0.66 ma, and $r_{be} = 4.78\, \text{K}\Omega$. The incremental equivalent circuit then is

\[
G_{MB}^V = \frac{1}{1 + 24.81 \left[ \frac{1}{4.78} + \frac{1}{(121)(2.5||0.33)} \right]} = \frac{24.81}{24.81 + 4.78 + (121)(2.5||0.33)} \approx -9.28 \, (19.35\, \text{db})
\]
The PSpice netlist for the specified design is:

```
NAMEQ1
IC 6.76E-04
VBE 6.54E-01
VCE 6.07E+00

Problem 4
VS 1 0 AC 1
RS 1 2 1K
CI 2 3 {CVAL}
RB1 4 3 100K
RB2 3 0 33K
Q1 5 3 6 Q2N3904
RE1 6 0 2.5K
RE2 6 7 330
CE 7 0 1U
RC4 5 2.5K
VCC 4 0 DC 10

.LIB EVAL.LIB.AC DEC 20 100 100K
.PARAM CVAL = 20N
.STEP PARAM CVAL LIST 10N 20N
.PROBE
.OP
.END
```
5) Estimate the low-frequency voltage gain (mid-band gain, 3dB frequency) for the circuit shown. Then compute the response, and compare to the estimate. Q1 is 2N3904, and Q2 is 2N3906.

**Answer**

Calculate the Q1 bias parameters neglecting the Q2 base current:

\[
\begin{align*}
V_T &= 1.75V \\
RT &= 8.25\, \Omega \\
IE(Q1) &\approx 0.98\, mA \\
r_{be} &= 3.2\, \Omega
\end{align*}
\]

and use the calculated Q1 collector voltage to calculate the Q2 emitter current and rbe.

\[
IE(Q2) \approx 1.3\, mA \quad r_{be} = 2.42\, \Omega
\]

The incremental parameter equivalent circuit is then

\[
\begin{align*}
Y_{MB} &= \frac{1}{1+8.25\|3.2} \frac{8.25}{8.25+3.2} (-120) \frac{2.7}{2.42+2.7} (-120)(2.2\|3.3) \\
&= 2185 \, (66.8\, \text{db})
\end{align*}
\]

\[
\begin{align*}
T11 &= (0.1)[1+(8.25\|3.2)] = 0.33 \, \text{msec} \\
TE1 &= \left(\frac{5}{121}\right)[(121)(3.2+8.25\|1)] = 0.16 \, \text{msec} \\
TE2 &= \left(\frac{5}{121}\right)[(121)(1.5\|2.42+2.7)] = 0.2 \, \text{msec} \\
To2 &= (0.1)[2.2+3.3] = 0.55 \, \text{msec}
\end{align*}
\]

\[
\omega_{3\, \text{db}} \approx \frac{1}{0.33} + \frac{1}{0.16} + \frac{1}{0.2} + \frac{1}{0.55}
\]

\[
= 16.19 \, \text{Krad/sec} \, (2.58\, \text{kHz})
\]
Problem 5

![Circuit Diagram]

<table>
<thead>
<tr>
<th>NODE</th>
<th>VOLTAGE</th>
</tr>
</thead>
<tbody>
<tr>
<td>(1)</td>
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<tr>
<td>(3)</td>
<td>1.6949</td>
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<tr>
<td>(4)</td>
<td>10.0000</td>
</tr>
<tr>
<td>(5)</td>
<td>7.2540</td>
</tr>
<tr>
<td>(6)</td>
<td>1.0304</td>
</tr>
<tr>
<td>(7)</td>
<td>2.9746</td>
</tr>
<tr>
<td>(8)</td>
<td>7.9626</td>
</tr>
<tr>
<td>(9)</td>
<td>0.0000</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>NAME</th>
<th>Q1</th>
<th>Q2</th>
</tr>
</thead>
<tbody>
<tr>
<td>MODEL</td>
<td>Q2N3904</td>
<td>Q2N3906</td>
</tr>
<tr>
<td>IC</td>
<td>1.02E-03</td>
<td>-1.35E-03</td>
</tr>
<tr>
<td>VBE</td>
<td>6.64E-01</td>
<td>-7.09E-01</td>
</tr>
<tr>
<td>VCE</td>
<td>6.22E+00</td>
<td>-4.99E+00</td>
</tr>
</tbody>
</table>

![Graph]

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revised
6) Estimate the low-frequency voltage gain (mid-band gain, 3db frequency) for the circuit shown. Compute the response, and compare to the estimate.

Answer
The DC bias calculation is made as described in a previous note.

\[ I_0 = I_{CQ1} \left[ \frac{6.8}{120} + \frac{150}{120} (0.22) \frac{121}{120} \right] - 0.7 - 0.7 \]
\[ I_{CQ1} = 1.04 \text{ mA} \]
\[ r_{be} = 3K\Omega \]
\[ I_{EQ2} = \frac{1.0 - (1.04)(6.8) - 0.7 + 1.04}{1.8} = 1.25 \text{ mA} \]
\[ r_{be} = 2.5K\Omega \]

The incremental parameter equivalent circuit is then as shown:

\[ G_{MB} = \frac{1}{1+150K||[3+(121)(.22)]} \frac{150K}{150K+[3+(121)(.22)]} (-120) \frac{6.8}{6.8+2.5} (-120)(3.3||10) \]
\[ = 847.7 \text{ (58.6 dB)} \]

\[ T_i = 0.1\{1+150K||[3+(121)(.22)]\} \]
\[ = 2.6 \text{ msec} \]
\[ T_o = 0.1(3.3+10) = 1.3 \text{ msec} \]

Determining the Thevenin resistance 'seen' by the second stage emitter capacitor is somewhat more involved because of the 150K\Omega resistor. However not for that for the computation the other capacitances are short-circuited, simplifying the calculation. Actually the influence of the 150K\Omega can be neglected for the calculation; the argument for this is that the current through the 1.8K\Omega emitter resistor clearly is more than an order of magnitude larger than the current in the 150K\Omega. (Or use PSpice to verify this.) Hence
\[ T = \frac{20}{121} \cdot \frac{[(121)(1.8)]}{[(2.5+6.8)]} \]

\[ \omega_{-3db} \approx \frac{1}{2.6} \cdot \frac{1}{1.3} \cdot \frac{1}{1.47} \]

\[ = 1.83 \text{ Krad/sec} \quad (290 \text{ Hz}) \]

A PSpice netlist to compute the frequency response follows.

**Problem 6**

```plaintext
VS 1 0 AC 1
RS 1 2 1K
CI 2 3 0.1U
Q1 4 3 9 Q2N3904
RC1 5 4 6.8K
RE1 9 0 220
Q2 6 4 7 Q2N3904
RC2 5 6 3.3K
RE2 7 0 1.8K
CE2 7 0 20U
RF 3 7 150K
CO 6 8 0.1U
RL 8 0 10K
VCC 5 0 DC 10

.LIB EVAL.LIB
.AC DEC 20 100 100K
.PROBE
.OP
.END
```

**NODE VOLTAGE**

| (1) | 0.0000 | (2) | 0.0000 | (3) | 0.9017 | (4) | 2.7336 |
| (5) | 10.0000 | (6) | 6.2147 | (7) | 2.0654 | (8) | 0.0000 |

**NAME**

| Q1 | Q2 |
| Q2N3904 | Q2N3904 |

**MODEL**

| IC | IC |
| 1.06E-03 | 1.15E-03 |
| VBE | VBE |
| 6.67E-01 | 6.68E-01 |
| VCE | VCE |
| 2.50E+00 | 4.15E+00 |
PROBLEMS (high-frequency)

6) Estimate the transresistance (V$_{\text{out}}$/I$_{\text{in}}$) frequency response for the incremental circuit shown. Compute the frequency response and compare with the estimate.

Answer

\[ T_{bc} = \frac{0.01}{3 + \frac{1}{10.89}} = 10.89 \mu\text{sec} \]
\[ T_{be} = 3 \mu\text{sec} \]
\[ \omega_{3\text{db}} = \frac{1}{3 + 10.89} = 0.072 \text{MegRad/sec} (11.467 \text{KHz}) \]
\[ G_{MB}^z = (3K)(0.06)(-6K) = -1.08 \times 10^6 (120.7 \text{db}) \]

*Prob 6
IS  0  1  AC  1
RBE 1  0  3K
CBE 1  0  1N
CBC 1  2  10P
G1  2  0  0.06
RL  2  0  6K
.PROBE
.AC DEC 20 1K 100K
.END
7) Estimate the transresistance \((V_{out}/I_{in})\) frequency response for the incremental circuit shown. Compute the frequency response and compare with the estimate.

\[
\begin{align*}
\text{gm} &= 60 \text{ millimho} \\
&= \text{(both devices)}
\end{align*}
\]

**Answer**

\[
\begin{align*}
\kappa_{MB}^2 &= (3)(-60) \frac{6}{6+14.1} (-120)(3.3K) \\
&= 21.28 \Omega \text{ (146.5db)}
\end{align*}
\]

The open-circuit time constants are:
- The base-emitter time constant for the first stage is (by inspection)
  \(T_{be1} = 3 \mu\text{sec}\)
- The (reduced) circuit for calculating the base-collector time constant of the first stage is drawn below. Apply a 1 ampere current source (not shown) at the capacitor terminals and calculate the terminal voltage; this provides the Thevenin resistance 'seen' by the capacitor. The calculation is simplified on transforming the emitter resistance of the second stage into the base as shown.

\[
\begin{align*}
T_{bc1} &= (0.01) \left\{ 3 + \left[ (1+3)(60) \right] \left[ 6 \left[ 2 + (121)(0.1) \right] \right] \right\} \\
&= 7.63 \mu\text{sec}
\end{align*}
\]
* The next calculation is for the base time constant of the second stage. The reduced circuit used for this calculation is:

\[ T_{be2} = \left( \frac{1}{6} \right) \left[ \frac{1}{6 + 14.1} \right] = 4.2 \mu\text{sec} \]

* The (reduced) circuit for calculating the base-collector time constant of the second stage is drawn below.

\[ T_{bc2} = (0.01) \left\{ \left( \frac{6}{3.3} \right) + \left[ 1 + \left( \frac{6}{6 + 14.1} \right) \right] (3.3) \right\} \]

\[ = 1.26 \mu\text{sec} \]

* The output time constant for the second stage is (by inspection)

\[ T_{be2} = (2)(3.3) = 6.6 \mu\text{sec} \]

\[ \omega_{3\text{dB}} \approx \frac{1}{3 + 7.63 + 4.2 + 1.26 + 6.6} \]

\[ = 0.044 \text{MHz/\text{sec}} \ (7 \text{KHz}) \]
8) The 2N3904 BJT emitter current is approximately 2ma. Use this circuit in a PSpice analysis to determine a nominal value for the gain-bandwidth product.

Answer
*Prob 8
VS 1 0 AC 1  
RS 1 2 100  
Cl 2 3 100U  
r1 4 2 33K  
r2 3 0 8.2K  
Q1 4 3 5 Q2N3904  
RE 5 0 1K  
CE 5 0 100U  
VCC 4 0 DC 10  
.PROBE  
.OP  
.LIB EVAL.LIB  
.AC DEC 20 100K 1000MEG  
.END

9) Estimate the voltage gain ($V_{out}/V_{in}$) frequency response for the incremental circuit shown. Compute the frequency response and compare with the estimate. Assume $C_{bc} = 4pF$ (max. value identified from manufacturer’s specifications) and a (nominal) gain-bandwidth product of 350 MHz.
Calculate the DC operating point, and the associated incremental parameter base resistance. Also estimate the base-emitter capacitance.

The high-frequency incremental parameter circuit examined is

\[ G_{MB} = \frac{1}{1 + (7.67)[3.4 + (121)(2.2)(0.1)]} \approx \frac{7.67}{7.67 + [3.4 + (121)(2.2)(0.1)](-120)(3.9||3.9)} = -13 \ (22.3\text{db}) \]

Consider first the open circuit time constant for the base-emitter capacitor. Replace the 16pF capacitor by a source (a unit current source is convenient) to calculate the Thevenin resistance 'seen' by the source; this is 210Ω, and the associated open circuit time constant is 0.003 µsec.

The time constant calculations for the other two capacitors active at high frequencies are shown next. Note that the external 5pF feedback capacitance is added to the intrinsic transistor capacitance.
The estimated high-frequency roll-off is

\[
\omega_{3\text{db}} \approx \frac{1}{0.003 + 0.16 + 0.195} = 2.18 \text{ MRad/sec (448 KHz)}
\]

\[
T_f = 0.1 \cdot (3.9/2) = 0.195 \mu\text{sec}
\]

The estimated high-frequency roll-off is

\[
\omega_{3\text{db}} \approx \frac{1}{0.6 + 0.78 + 0.634} = 4.5 \text{ KRad/sec (720 Hz)}
\]

A PSpice netlist to compute the frequency response follows.

Problem 9

<table>
<thead>
<tr>
<th>VS</th>
<th>1</th>
<th>0</th>
<th>AC</th>
<th>1</th>
<th>CO</th>
<th>5</th>
<th>8</th>
<th>0.1U</th>
</tr>
</thead>
<tbody>
<tr>
<td>RS</td>
<td>1</td>
<td>2</td>
<td>1K</td>
<td></td>
<td>RL</td>
<td>8</td>
<td>0</td>
<td>3.9K</td>
</tr>
<tr>
<td>CI</td>
<td>2</td>
<td>3</td>
<td>0.1U</td>
<td></td>
<td>CL</td>
<td>8</td>
<td>0</td>
<td>0.1N</td>
</tr>
<tr>
<td>RB1</td>
<td>4</td>
<td>3</td>
<td>33K</td>
<td></td>
<td>VCC</td>
<td>4</td>
<td>0</td>
<td>DC 12</td>
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<tr>
<td>RB2</td>
<td>3</td>
<td>0</td>
<td>10K</td>
<td></td>
<td>.LIB</td>
<td>EVAL.LIB</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Q1</td>
<td>5</td>
<td>3</td>
<td>6</td>
<td>Q2N3904</td>
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**NODE VOLTAGE**

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