Chapter 6

BJT Amplifiers

6.1 Amplifier Operations [5], [7]

6.1.1 AC Quantities

In the previous chapters, dc quantities were identified by nonitalic uppercase (capital) subscripts such as $I_C$, $I_E$, $V_C$, and $V_{CE}$. Lowercase italic subscripts are used to indicate ac quantities of rms, peak, and peak-to-peak currents and voltages: for example, $i_c$, $i_e$, $i_b$, $v_c$, and $v_{ce}$ (rms values are assumed unless otherwise stated). Instantaneous quantities are represented by both lowercase letters and subscripts such as $i_c$, $i_e$, $i_b$, and $v_{ce}$. Moreover, $R_c$ is the ac collector resistance, and $R_C$ is the dc collector resistance.

![Figure 6.1 DC and AC quantities.](image)

Figure 6.1 DC and AC quantities.
6.1.2 The Linear Amplifier

A linear amplifier provides amplification of a signal without any distortion so that the output signal is an amplified replica of the input signal. A voltage-divider biased transistor with a sinusoidal ac source capacitively coupled to the base through C₁ and a load capacitively coupled to the collector through C₂ is shown in Figure 6–2. The coupling capacitors block dc and thus prevent the internal source resistance, Rₛ, and the load resistance, Rₗ, from changing the dc bias voltages at the base and collector. The capacitors ideally appear as shorts to the signal voltage. The sinusoidal source voltage causes the base voltage to vary sinusoidally above and below its dc bias level, V₉. The resulting variation in base current produces a larger variation in collector current because of the current gain of the transistor.

![Figure 6.2 An amplifier with voltage-divider bias driven by an ac voltage source with an internal resistance, Rₛ. [5]](image)

As the sinusoidal collector current increases, the collector voltage decreases. The collector current varies above and below its Q-point value, I₉, in phase with the base current. The sinusoidal collector-to-emitter voltage varies above and below its Q-point value, Vₑ, 180° out of phase with the base voltage, as illustrated in Figure 6.2. A transistor always produces a phase inversion between the base voltage and the collector voltage.
A Graphical Picture:

The operation just described can be illustrated graphically on the ac load line, as shown in Figure 6.3. The sinusoidal voltage at the base produces a base current that varies above and below the Q-point on the ac load line, as shown by the arrows. Lines projected from the peaks of the base current, across to the $I_C$ axis, and down to the $V_{CE}$ axis, indicate the peak-to-peak variations of the collector current and collector-to-emitter voltage.

![Graphical operation of the amplifier showing the variation of the base current, collector current, and collector-to-emitter voltage about their dc Q-point values. $I_b$ and $I_c$ are on different scales. [5]](image)

Figure 6.3 Graphical operation of the amplifier showing the variation of the base current, collector current, and collector-to-emitter voltage about their dc Q-point values. $I_b$ and $I_c$ are on different scales. [5]

6.2 BJT Small-Signal models [5], [7]

6.2.1 AC equivalent model

To visualize the operation of a transistor in an amplifier circuit, it is often useful to represent the device by a model circuit. A transistor model circuit uses various internal transistor parameters to represent its operation. Transistor models are described in this section based on hybrid-p model, simplified hybrid-p model and $r_e$ transistor model.
6.2.1.1 The hybrid-\(\pi\) model

\begin{equation}
\beta = \frac{i_C}{i_b} = \frac{g_m v_{x}}{i_b} = g_m r_{\pi}
\end{equation}

- \(r_b\) is very small.
- \(r_{\mu}\) and \(r_{x}\) are very large.
- At low frequencies, \(c_{\pi}\) and \(c_{\mu}\) act like open circuits.

\begin{align*}
r_{\pi} &= \frac{\beta}{g_m} \\
g_m &= \frac{I_{\text{CO}}}{V_T} \\
V_T &= \text{Thermal voltage} = 26 \text{ mV}
\end{align*}

Figure 6.4 The hybrid-\(\pi\) model.

6.2.1.2 The simplified hybrid-\(\pi\) model

\begin{equation}
\beta = \frac{i_C}{i_b} = \frac{g_m v_{x}}{i_b} = g_m r_{\pi}
\end{equation}

Figure 6.5 The simplified hybrid-\(\pi\) model.
6.2.1.3 The $r_e$ transistor model (1)

The simplified-$r_e$ transistor model

In this model:

$$r_e = \frac{V_T}{I_E} = \frac{26 \text{ mV}}{I_E}$$

$$r_e \approx \infty \Omega$$

Figure 6.6 The $r_e$ transistor model (1). [7]

The comparison between the simplified-$r_e$ transistor model (1) and the simplified hybrid-$\pi$ model is shown in Figure 6.7.

Figure 6.7 2 ac transistor models. [7]
Therefore, we can conclude that

\[ \beta r_e = r_n, \quad r_e \approx \frac{1}{g_m} = \frac{V_T}{I_{CQ}} \]

\[ \beta I_b = g_m v_n \]

Note that this \( r_e \) transistor model (1) is used for common-emitter amplifier and common-collector amplifier.

6.2.1.4 The \( r_e \) transistor model (2)

![The \( r_e \) transistor model (2)](image)

Figure 6.8 The \( r_e \) transistor model (2) [7]

Note that this \( r_e \) transistor model (2) is used for common-base amplifier.
6.2.2 Comparison of the AC Beta ($\beta_{ac}$) to the DC Beta ($\beta_{dc}$)

For a typical transistor, a graph of $I_C$ versus $I_B$ is nonlinear (Figure 6.9). At different points on the nonlinear curve, the ratio $\Delta I_C/\Delta I_B$ will be different, and may also differ from the $I_C/I_B$ ratio at the Q-point. Since $\beta_{DC} = I_C/I_B$ and $\beta_{ac} = \Delta I_C/\Delta I_B$, the values of these two quantities can differ slightly.

Figure 6.9 $I_C$-versus-$I_B$ curve illustrates the difference between $\beta_{DC}$ and $\beta_{ac}$. [5]

6.2.3 The General Amplifier Model

The ideal amplifier:
1. Infinite gain
2. Infinite input impedance ($Z_i$)
3. Zero output impedance ($Z_o$)

Figure 6.10 The general amplifier model [7]
Amplifier Properties:

Gain(A): The gain of an amplifier is the ratio of the circuit’s output to input. There are 3 types of gain:

- Voltage gain ($A_v$) = $V_o/V_i$
- Current gain ($A_i$) = $I_o/I_i$
- Power gain ($A_p$) = $P_o/P_i = A_vA_i$

6.3 BJT Amplifier Configurations [5], [7]
There are three BJT amplifier configurations, see Figure 6.11-6.13.

Figure 6.11 Common-emitter amplifier.

Figure 6.12 Common-base amplifier.
6.4 The Common-Emitter with voltage-divider bias [5], [7]

Figure 6.14 shows a common-emitter amplifier with voltage-divider bias and coupling capacitors, $C_1$ and $C_3$, on the input and output and a bypass capacitor, $C_2$, from emitter to ground. The circuit has a combination of dc and ac operation. The input signal, $V_{in}$, is capacitively coupled into the base, and the output signal, $V_{out}$, is capacitively coupled from the collector. The amplified output is $180^\circ$ out of phase with the input.
**DC Analysis:**

To analyze the amplifier, the dc bias values must first be determined. To do this, a dc equivalent circuit is developed by replacing the coupling and bypass capacitors with opens (→ a capacitor appears open to dc). DC equivalent circuit for the amplifier in Figure 6.14 is shown in Figure 6.15.

![DC equivalent circuit for the amplifier](image)

Figure 6.15 DC equivalent circuit for the amplifier in Figure 6.14. [5]

**The AC Equivalent Circuit:**

To analyze the ac signal operation of an amplifier, an ac equivalent circuit is developed as follows:

1. The capacitors $C_1$, $C_2$, and $C_3$ are replaced by short circuit.

2. The dc source is replaced by a ground and is called ac ground.

The ac equivalent circuit is shown in Figure 6.16. Note that both $R_C$ and $R_1$ have connected to ac ground because in the actual circuit, they are connected to $V_{CC}$ which is ac ground. In ac analysis, the ac ground and the actual ground are treated as the same point electrically. *Ground is the common point in the circuit.*
From Figure 6.16, we can use the simplified-\( r_e \) transistor model (1) to analyze this common-emitter amplifier with voltage-divider bias, and then the equivalent circuit is shown in Figure 6.17.

**Figure 6.16** AC equivalent circuit for the amplifier in Figure 6.14. [5]

**Figure 6.17** AC equivalent circuit for the amplifier in Figure 6.14 using the simplified-\( r_e \) transistor model (1) [7]
Here, \( R' = R_i \| R_2 = \frac{R_1 R_2}{R_1 + R_2} \)

To find \( Z_i \), \( Z_i = R' \| \beta r_e \)

To find \( Z_o \): with \( V_i \) set to 0 V, resulting in \( I_b = 0 \mu A \) and \( \beta I_b = 0 \) mA, resulting in an open-circuit for \( \beta I_b \).

\[ Z_o = R_C \]

\[ \begin{align*}
V_o &= -(\beta I_b)R_C \quad \text{and} \quad I_b = \frac{V_i}{\beta r_e} \\
\text{so that} \quad V_o &= -\beta \left( \frac{V_i}{\beta r_e} \right) R_C = -\frac{V_i R_C}{r_e} \\
\text{and} \quad A_v &= \frac{V_o}{V_i} = -\frac{R_C}{r_e} \quad \Rightarrow \quad \text{The negative sign reveals a 180° phase shift between } V_o \text{ and } V_i
\end{align*} \]

To find current gain (\( A_i \)):

\[ A_i = \frac{I_o}{I_i} = \frac{\beta I_b}{I_i} = \beta \left( \frac{Z_i}{V_i} \right) = \frac{\beta I_b (R' \| \beta r_e)}{V_i} \]

if \( R' \gg \beta r_e \), \( R' \| \beta r_e \approx \beta r_e \) and \( I_i \approx I_b \), then \( V_i \approx I_b (\beta r_e) \)

\[ \therefore A_i \approx \frac{\beta I_b (\beta r_e)}{I_b (\beta r_e)} = \beta \quad \Rightarrow \quad \text{Because of the positive sign, } I_o \text{ and } I_i \text{ are in phase.} \]
Example 1: For the network of Figure 6.19. Determine $r_e$, $Z_i$, $Z_o$ and $A_v$.

Figure 6.19 For Example 1. [7]

Solution:

Step 1: DC analysis

$>>$ This circuit is voltage-divider biased transistor circuit

\[ V_{\text{TH}} = \frac{R_2}{R_1 + R_2} V_{\text{CC}} = \frac{8.2}{56 + 8.2} \times 22 = 2.81 \text{ V} \]

\[ R_{\text{TH}} = \frac{R_1}{R_2} = \frac{56}{8.2} = 7.15 \text{ k\Omega} \]

\[ I_B = \frac{V_{\text{TH}} - V_{\text{BE}}}{R_{\text{TH}} + (\beta_{DC} + 1)R_E} = \frac{2.81 - 0.7}{7.15 \text{ k\Omega} + (90 + 1)1.5 \text{ k\Omega}} = 14.69 \mu\text{A} \]

\[ I_C = \beta I_E = 100 \times 14.69 \mu\text{A} = 1.469 \text{ mA} \]

\[ I_E = I_B + I_C = 1.484 \text{ mA} \]
Step 2: AC analysis

\[ r_e = \frac{26 \text{ mV}}{1.484 \text{ mA}} = 17.52 \Omega \]

\[ R' = R_1 \parallel R_2 = (56k\Omega) \parallel (8.2k\Omega) = 7.15k\Omega \]

\[ Z_i = R' \parallel \beta r_e = (7.15 \text{ k}\Omega) \parallel (90)(17.52 \Omega) = 7.15 \text{ k}\Omega \parallel 1.577 \text{ k}\Omega = 1.292 \text{ k}\Omega \]

\[ Z_o = R_C = 6.8 \text{ k}\Omega \]

\[ A_v = -\frac{R_C}{r_e} = -\frac{6.8 \text{ k}\Omega}{17.52 \Omega} = -388.13 \]

### 6.5 The Common-Emitter fixed-bias configuration [5], [7]

Figure 6.20 shows a common-emitter amplifier fixed-bias configuration and coupling capacitors, C1 and C2 on the input and output. \(V_{CC}\) is DC voltage source. \(V_{in}\) is AC voltage source.

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Figure 6.20 Common-emitter fixed-bias configuration. [7]
DC Analysis:

\[C_1 \text{ and } C_2 \text{ are replaced by open circuit. Then DC equivalent circuit for the amplifier in Figure 6.20 is shown in Figure 6.21.}\]

\[\text{Figure 6.21 DC equivalent circuit for the amplifier in Figure 6.20. [7]}\]

AC Analysis:

\[V_{CC} \text{ is replaced by virtual ground. And } C_1 \text{ and } C_2 \text{ are replaced by short circuit. Then AC equivalent circuit for the amplifier in Figure 6.20 is shown in Figure 6.21. We can use the simplified-re transistor model (1) to analyze this common-emitter fixed-bias configuration amplifier, and then the equivalent circuit is shown in Figure 6.23.}\]

\[\text{Figure 6.22 AC equivalent circuit for the amplifier in Figure 6.20. [7]}\]
Figure 6.23 Substituting the $r_e$ transistor model into the network of Figure 6.22. [7]

For this circuit:

$$Z_i = R_B \parallel \beta r_e$$

$$Z_o = R_C \quad >> \text{Assume } V_i = 0, \text{ then } I_i = I_b = 0, \text{ resulting in an open-circuit for } \beta I_b$$

To find voltage gain ($A_v$):

$$V_o = - (\beta I_b) R_C \quad \text{and} \quad I_b = \frac{V_i}{\beta r_e}, \quad \text{so that} \quad V_o = - \beta \left( \frac{V_i}{\beta r_e} \right) R_C = - \frac{V_i R_C}{r_e}$$

and

$$A_v = \frac{V_o}{V_i} = - \frac{R_C}{r_e} \quad \rightarrow \quad \text{The negative sign reveals a 180° phase shift between } V_o \text{ and } V_i$$

To find current gain ($A_i$):

$$A_i = \frac{I_o}{I_i} = \frac{\beta I_b}{I_i} = \beta I_b \left( \frac{Z_i}{V_i} \right) = \frac{\beta I_b (R_B \parallel r_e)}{V_i}$$

if $R_B >> \beta r_e$, $R_B \parallel r_e \cong \beta r_e$ and $I_i \cong I_b$, then $V_i \cong I_b (\beta r_e)$

$$\therefore A_i \cong \frac{\beta I_b (\beta r_e)}{I_b (\beta r_e)} = \beta \quad \rightarrow \quad \text{Because of the positive sign, } I_o \text{ and } I_i \text{ are in phase.}$$
Example 2: For the network of Figure 6.25. Determine $r_e$, $Z_i$, $Z_o$ and $A_v$.

Solution: Step 1: DC analysis

As shown in Figure 6.26, this circuit is base bias transistor circuit. Therefore,

\[
I_B = \frac{V_{CC} - V_{BE}}{R_B} = \frac{12V - 0.7V}{470 \text{k}\Omega} = 24.04 \mu\text{A}
\]

\[
I_C = \beta I_B = 100 \times 24.04 \mu\text{A} = 2.404 \text{mA}
\]

\[
I_E = I_B + I_C = 2.428 \text{mA}
\]
Step 2: AC analysis

\[ r_e = \frac{26 \text{ mV}}{2.404 \text{ mA}} = \frac{26 \text{ mV}}{2.404 \times 10^{-3} \text{ A}} = 10.815 \Omega \]

\[ Z_i = R_B \parallel \beta r_e = 470 \text{k\Omega} \parallel (100) \times 10.815 \text{\Omega} = 1.079 \text{k\Omega} \]

\[ Z_o = R_C = 3 \text{k\Omega} \]

\[ A_v = -\frac{R_C}{r_e} = -\frac{3 \text{ k\Omega}}{10.815 \text{\Omega}} = -277.39 \]

### 6.6 The Common-Emitter amplifier with an emitter resistor [7]

![Common-Emitter amplifier with R_E](image7)

Figure 6.27 Common-Emitter amplifier with R_E [7]
The most fundamental of unbypassed configurations appears in Figure 6.27. The $r_e$ transistor model (1) is substituted in Figure 6.28. In this case, $R_E$ is connected in unbypassed situation.

Figure 6.28 Substituting the $r_e$ transistor model into the network of Figure 6.27. [7]

Applying KVL to the input side;

$$V_i = I_b \beta r_e + I_a R_E \quad \text{or} \quad V_i = I_b \beta r_e + (\beta + 1) I_b R_E$$

And the input impedance looking into the network to the right of $R_E$ is

$$Z_b = \frac{V_i}{I_b} = \beta r_e + (\beta + 1) R_E \approx \beta (r_e + R_E), \quad \text{assume} \ \beta \approx \beta + 1$$

Then

$$Z_i = R_E \parallel Z_b$$

and

$$Z_o = R_C \quad \gg \quad \text{Assume} \ V_i = 0, \ \text{then} \ I_i = I_b = 0, \ \text{resulting in an open-circuit for} \ \beta I_b$$

To find voltage gain ($A_v$):

$$V_o = -(\beta I_b) R_C, \ \text{and} \ I_b = \frac{V_i}{Z_b}, \ \text{so that} \ V_o = -\beta \left( \frac{V_i}{Z_b} \right) R_C$$

then

$$A_v = \frac{V_o}{V_i} = -\frac{\beta R_C}{Z_b}$$

Substituting

$$Z_b \approx \beta (r_e + R_E) \quad \text{gives} \quad A_v = \frac{V_o}{V_i} = -\frac{R_C}{r_e + R_E}$$
Example 3: For the network of Figure 6.29, determine $r_e$, $Z_i$, $Z_o$ and $A_v$.

Solution:

Step 1: DC analysis

\[ V_{cc} = I_B R_B + V_{BE} + I_E R_E \]
\[ = I_B R_B + V_{BE} + (\beta + 1) I_B R_E \]

\[ \therefore I_B = \frac{V_{cc} - V_{BE}}{R_B + (\beta + 1) R_E} = \frac{20V - 0.7V}{470k\Omega + (121)0.56k\Omega} \]
\[ = 35.89 \mu A \]

\[ I_E = (\beta + 1) I_B = (121)(35.89\mu A) = 4.34mA \]

Step 2: AC analysis

\[ r_e = \frac{26 \text{ mV}}{I_E} = \frac{26 \text{ mV}}{4.34 \text{ mA}} = 5.99 \Omega \]

Here, \[ Z_b = \beta r_e + (\beta + 1) R_E \]
\[ = 120 \times 5.99 \Omega + (120 + 1) \times 560 \Omega = 68.48k\Omega \]
Therefore \[ Z_i = R_B \parallel Z_E = 470 \text{k}\Omega \parallel 68.48 \text{k}\Omega = 59.77 \text{k}\Omega \]

and \[ Z_o = R_C = 2.2 \text{k}\Omega \]

\[ A_v = \frac{V_o}{V_i} = -\frac{\beta R_C}{Z_b} = -\frac{120 \times 2.2 \text{k}\Omega}{68.48 \text{k}\Omega} = -3.855 \]

***If we assume \[ Z_b \approx \beta (r_e + R_E) = 120 \times (5.99 \Omega + 560 \Omega) = 67.92 \text{k}\Omega \]

then \[ A_v = \frac{V_o}{V_i} = -\frac{R_C}{r_e + R_E} = \frac{2.2 \text{k}\Omega}{(5.99 + 560) \Omega} = -3.887 \]

Another variation of an emitter-bias configuration is the swamped common-emitter amplifier. For the DC analysis, the emitter resistance is \( R_{E1} + R_{E2} \), whereas for the AC analysis, the resistor \( R_E \) the emitter resistance is only \( R_{E1} \) and \( R_{E2} \) is bypassed by \( C_E \).

![Swamped common-emitter amplifier](image)

Figure 6.30 Swamped common-emitter amplifier. [7]
6.7 Effect of $R_L$ and $R_S$ [5], [7]

Figure 6.31 shows 3 types of amplifier configuration: (a) unloaded, (b) loaded and (c) loaded with a source resistance. From Figure 6.31-6.33, we can conclude that for the same configuration: $A_{vNL} > A_v > A_{vS}$.

\[ A_{vNL} = \frac{V_o}{V_i} \]

**Figure 6.31 Unloaded amplifier configuration. [7]**

\[ A_v = \frac{V_o}{V_i} \text{ with } R_L \]

**Figure 6.32 Loaded amplifier configuration. [7]**
Here, AC analysis for amplifier configuration: (c) loaded with a source resistance is shown in Figure 6.34.

$$A_{g5} = \frac{V_o}{V_s}$$

Figure 6.33 Loaded with a source resistance amplifier configuration. [7]

$$\hat{R_L} = R_C || R_L$$

Figure 6.34 Substituting the re transistor model into the network of Figure 6.33. [7]
The parallel combination of \( R'_L = R_C \| R_L \)
and \( V_o = -\beta I_b R'_L = -\beta I_b \left( R_C \| R_L \right) \)

with \( I_b = \frac{V_i}{\beta r_e} \)
gives \( V_o = -\beta I_b R'_L = -\beta \left( \frac{V_i}{\beta r_e} \right) \left( R_C \| R_L \right) \)

So that \( A_v = \frac{V_o}{V_i} = -\frac{R_C \| R_L}{r_e} \)

*** The only difference in \( A_v \) is the fact that \( R_C \) has been replaced by \( R_C \| R_L \)

The input impedance is \( Z_i = R_B \| \beta r_e \) as before.

And the output impedance \( Z_o = R_C \) as before.

To find overall voltage gain \( (A_{v_s}) \):

Using voltage-division: \( V_i = \frac{Z_i V_S}{Z_i + R_S} \)

and \( \frac{V_i}{V_S} = \frac{Z_i}{Z_i + R_S} \)

or \( A_{v_s} = \frac{V_o}{V_S} = \frac{V_o}{V_i} \times \frac{V_i}{V_S} = A_v \times \frac{Z_i}{Z_i + R_S} \)

So that \( A_{v_s} = \frac{Z_i}{Z_i + R_S} \times A_v \)
Example 4: Determine the total collector voltage and the total output voltage (dc and ac). Draw the waveforms of both voltages.

Figure 6.35 For Example 4. [5]

Solution: Two sets of calculations are necessary to determine the total collector voltage.

Step1: DC analysis → refer to the dc equivalent circuit in Figure 6.36.

Figure 6.36 For Example 4. [5]
Here,

\[ V_{\text{th}} = \frac{R_2}{R_1 + R_2} V_{cc} = \frac{10}{47 + 10} \times 10 = 1.754 \text{ V} \]

\[ R_{\text{th}} = R_1 / R_2 = 47 / 10 = 8.246 \text{ k}\Omega \]

\[ I_B = \frac{V_{\text{th}} - V_{\text{BE}}}{R_{\text{th}} + (\beta_{\text{DC}} + 1)R_E} = \frac{V_{\text{th}} - V_{\text{BE}}}{R_{\text{th}} + (\beta_{\text{DC}} + 1)(R_{E1} + R_{E2})} \]

\[ = \frac{1.754 - 0.7}{8.246 \text{ k}\Omega + (150 + 1)(0.47 + 0.47) \text{ k}\Omega} = 7.02 \mu\text{A} \]

\[ I_C = \beta_{\text{DC}} I_B = 150 \times 7.02 \mu\text{A} = 1.053 \text{ mA} \]

\[ I_E = (\beta_{\text{DC}} + 1) I_B = 151 \times 7.02 \mu\text{A} = 1.06 \text{ mA} \]

\[ V_C = V_{cc} - I_C R_C = 10 - (1.053 \text{ mA})(4.7 \text{ k}\Omega) = 5.05 \text{ V} \]

**Step 2:** AC analysis → the ac analysis is based on the ac equivalent circuit in Figure 6.37.

Here, this circuit becomes common-emitter amplifier with an emitter resistor \( R_{E1} \) and a load resistor \( R_L \). And

\[ r_e = \frac{26 \text{ mV}}{I_E} = \frac{26 \text{ mV}}{1.06 \text{ mA}} = 24.53 \text{ \Omega} \]
Substituting the $r_e$ transistor model into the network of Figure 6.37, then we can obtain the circuit shown in Figure 6.38.

If we assume $Z_b \approx \beta (r_e + R_{E1})$, then

$$A_v = \frac{V_o}{V_i} = -\frac{R_C}{r_e + R_{E1}} = -\frac{4.7 \text{ k}\Omega}{24.53 \text{ k}\Omega + 470 \text{ } \Omega} = -8.64$$

and

$$A_{v_s} = \frac{Z_i}{Z_i + R_s} \times A_v$$

Here,

$$Z_i = R_E||Z_b$$

$$Z_b \approx \beta_{ac} (r_e + R_{E1}) = 175(24.53 + 470) = 86.54 \text{ k}\Omega$$

$$R_E = R_1||R_2 = 47||10 = 8.246 \text{ k}\Omega$$

$$\therefore Z_i = R_E||Z_b = 8.246||86.54 = 7.529 \text{ k}\Omega$$
Step 3: collector voltage and output waveform.

The total collector voltage is the signal voltage of 113.14 mV_p riding on a DC level (V_C) of 5.05 V.

\[
A_v = \frac{7.529 \text{k}\Omega}{7.529 \text{k}\Omega + 600 \Omega} \times (-8.64) = -8.00 = \frac{V_o}{V_s} = \frac{V_c}{V_s}
\]

The AC source produced 10 mVrms

\[
\therefore V_c = A_v V_s = -8.00 \times 10 \text{ mVrms} = -80 \text{ mVrms} = -113.14 \text{ mVp}
\]

Note that the coupling capacitor, C_3, keeps the dc level from getting to the output. Therefore, V_{out} is equal to the ac portion of the collector voltage (V_{out} = 113.14 mV_p). Finally, the waveform of V_{out} is shown in Figure 6.40.
Example 5: Determine the total collector voltage and the total output voltage (dc and ac). Draw the waveforms of both voltages.

Figure 6.41 For Example 5.
**Solution:** Two sets of calculations are necessary to determine the total collector voltage.

**Step 1:** DC analysis → refer to the dc equivalent circuit in Figure 6.42.

![DC equivalent circuit](image)

**Figure 6.42 For Example 5.**

\[
I_B R_1 + V_{BE} + I_E \left( R_{E1} + R_{E2} \right) = V_{CC}
\]

\[
I_B R_1 + V_{BE} + (\beta_{DC} + 1)I_B \left( R_{E1} + R_{E2} \right) = V_{CC}
\]

\[
I_B = \frac{V_{CC} - V_{BE}}{R_1 + (\beta_{DC} + 1) \left( R_{E1} + R_{E2} \right)}
\]

\[
= \frac{20 - 0.7}{1.6 \times 10^6 + (100 + 1)(1.5 \times 10^3 + 1.8 \times 10^3)}
\]

\[
= 9.983 \mu A
\]

\[
I_C = \beta_{DC} I_B = 100 \times 9.983 \mu A = 0.998 mA
\]

\[
I_E = (\beta_{DC} + 1)I_B = 101 \times 9.983 \mu A = 1.008 mA
\]

\[
V_C = V_{CC} - I_C R_C = 20 - \left( 0.998 mA \right) \left( 10 \times 10^3 \Omega \right)
\]

\[
= 10.02 V
\]
Step 2: AC analysis → the ac analysis is based on the ac equivalent circuit in Figure 6.43.

For Example 5. Here, this circuit becomes common-emitter amplifier with an emitter resistor $R_{E1}$ and a load resistor $R_L$. And

$$r_e = \frac{26 \text{ mV}}{I_E} = \frac{26 \text{ mV}}{1.008 \text{ mA}} = 25.794 \text{ Ω}$$

Substituting the $r_e$ transistor model into the network of Figure 6.43, then we can obtain the circuit shown in Figure 6.44.
If we assume \( Z_b \approx \beta (r_e + R_{E1}) \), then

\[
A_v = \frac{V_o}{V_i} \equiv - \frac{R_C}{r_e + R_{E1}} = -\frac{10 \text{ k}\Omega \parallel 50 \text{ k}\Omega}{25.794 \Omega + 1.5 \text{ k}\Omega} = -5.46
\]

and

\[
A_{v_s} = \frac{Z_i}{Z_i + R_s} \times A_v
\]

Here,

\[
Z_i = R_E \parallel Z_b
\]

\[
Z_b \approx \beta_{ac} (r_e + R_{E1}) = 120(25.794 \Omega + 1.5 \text{ k}\Omega) = 183.095 \text{ k}\Omega
\]

\[
R_E = R_1 = 1.6 \text{ M}\Omega
\]

\[
\therefore Z_i = R_E \parallel Z_b = 1.6 \text{ M}\Omega \parallel 183.095 = 164.294 \text{ k}\Omega
\]

Therefore,

\[
A_{v_s} = \frac{164.294 \text{ k}\Omega}{164.294 \text{ k}\Omega + 500 \Omega} \times (-5.46) = -5.443 = \frac{V_o}{V_s} = \frac{V_c}{V_s}
\]

The AC source produced 10 mVrms

\[
\therefore V_c = A_{v_s} V_s = -5.443 \times 10 \text{ mVrms} = -54.43 \text{ mVrms} = -76.982 \text{ mVp}
\]

**Step 3:** collector voltage and output waveform.

The total collector voltage is the signal voltage of 76.982 mV\(_p\) riding on a DC level (\(V_c\)) of 10.02 V.

\[
\therefore \text{Max } V_c = 10.02 \text{ V} + 76.982 \text{ mV} = 10.097 \text{ V}
\]

\[
\text{Min } V_c = 10.02 \text{ V} - 76.982 \text{ mV} = 9.943 \text{ V}
\]
Note that the coupling capacitor, $C_3$, keeps the dc level from getting to the output. Therefore, $V_{out}$ is equal to the ac portion of the collector voltage ($V_{out} = 76.982 \text{ mV}_p$). Finally, the waveform of $V_{out}$ is shown in Figure 6.46.

Output voltage waveform ($V_{out}$)

Figure 6.46 For Example 5.
6.8 Homework 9

1. Draw the DC equivalent circuit and the AC equivalent circuit for the unloaded amplifier in Figure 6.47. And then find $Z_i$ and $A_v$.

![Figure 6.47 For Problem 1. [5]](image)

2. Connect a bypass capacitor across $R_E$ in the amplifier in problem 1, and then find $Z_i$ and $A_v$.

3. Connect a 10 kΩ load resistor to the output in the amplifier in problem 1, and then find $Z_i$ and $A_v$. 
4. (a) Find the input impedance \( (Z_i) \) and the overall voltage gain of the amplifier shown in Figure 6.48.

(b) Determine the total collector voltage (dc and ac) and the total output voltage (dc and ac). Draw the waveforms of both voltages.

\[
\begin{align*}
\beta_{DC} &= 100 \\
\beta_{ac} &= 100 \\
R_1 &= 10 \text{k} \Omega \\
R_S &= 200 \text{ } \Omega \\
R_2 &= 200 \text{ } \text{k} \Omega \\
R_C &= 10 \text{ } \text{k} \Omega \\
R_3 &= 30 \text{ } \text{k} \Omega \\
R_{E1} &= 1 \text{ } \text{k} \Omega \\
R_{E2} &= 9 \text{ } \text{k} \Omega \\
V_{in} &= 20 \text{ mV}_{p-p} \\
+20 \text{ V} \\
R_L &= 60 \text{ } \text{k} \Omega \\
V_{out} & 
\end{align*}
\]
5. Determine the total collector voltage (DC and AC) and the total output voltage (DC and AC). Draw the waveforms of both voltages.

\[ \beta_{DC} = \beta_{ac} = 125 \]

\[ R_C = 5 \, k\Omega \]

\[ R_L = 20 \, k\Omega \]

\[ R_{E1} = 2 \, k\Omega \]

\[ R_{E2} = 8 \, k\Omega \]

\[ +V_{CC} +15 \, V \]

\[ +V_{out} \]

\[ -V_{FE} -15 \, V \]

\[ 100 \, mV_{rms} \]

\[ V_{in} \]

Figure 6.49 For Problem 5.
6. (a) Find the input impedance ($Z_i$) and the overall voltage gain of the amplifier shown in Figure 6.50.

(b) Determine the total base voltage (dc and ac) and the total output voltage (dc and ac). Draw the waveforms of both voltages.

$\beta_{DC} = \beta_{ac} = 150$

$R_1 = 1.5 \, \text{M}\Omega$

$V_{in}$

$R_S = 5 \, \text{k}\Omega$

$R_C = 10 \, \text{k}\Omega$

$V_{out}$

$R_L = 40 \, \text{k}\Omega$

$20 \, \text{mV}_{\text{rms}}$

Figure 6.50 For Problem 6.
7. Determine the total base voltage (DC and AC) and the total output voltage \( V_{out} \) (DC and AC). Draw the waveforms of both voltages. Using \( I_E = I_B + I_C \).

\[
\begin{align*}
R_S &= 300 \, \Omega \\
V_{in} &= 200 \, \text{mV}_{\text{rms}} \\
\beta_{DC} &= 100 \\
\beta_{ac} &= 120 \\
R_{E1} &= 2 \, \text{k}\Omega \\
R_{E2} &= 3 \, \text{k}\Omega \\
R_L &= 30 \, \text{k}\Omega \\
V_{in} &= + \, 40 \, \text{V} \\
\end{align*}
\]

Figure 6.51 For Problem 7.
8. Determine the total base voltage (DC and AC) and the total output voltage (V_{out}) (DC and AC). Draw the waveforms of both voltages. Using I_E = I_B + I_C.

(25 marks)

\[ \beta_{DC} = 100 \]
\[ \beta_{ac} = 110 \]

Figure 6.52 For Problem 8.
6.9 The Common-Collector amplifier (Emitter Follower) [7]

The most common collector configuration appears in Figure 6.53, the network is referred to as an emitter-follower. The output voltage is always slightly less than the input signal due to the drop from base to emitter, but the approximation $A_v \approx 1$ is usually a good one. Unlike the collector voltage, the emitter voltage is in phase with the signal $V_i$. That is, both $V_o$ and $V_i$ will attain their positive and negative peak values at the same time. The fact that $V_o$ “follows” the magnitude of $V_i$ with an in-phase relationship accounts for the terminology emitter-follower. Substituting the $r_e$ equivalent circuit into the network of Figure 6.53 will result in the network of Figure 6.54.

![Figure 6.53 Emitter-follower configuration.][7]

![Figure 6.54 Substituting $r_e$ transistor model into the network of Figure 6.53.][7]
To find $Z_4$:

The input impedance is $Z_i = R_E \parallel Z_b$

Here $Z_b = \frac{V_b}{I_b} = \frac{I_b \beta r_e + (\beta + 1)I_b R_E}{I_b} = \beta r_e + (\beta + 1)R_E$

Or $Z_b \equiv \beta (r_e + R_E)$

To find $Z_0$:

$I_b = \frac{V_i}{Z_b}$, and then $I_e = (\beta + 1)I_b = (\beta + 1)\frac{V_i}{Z_b}$

Substituting for $Z_b$ gives

$I_e = \frac{(\beta + 1)V_i}{\beta r_e + (\beta + 1)R_E}$

but $\beta + 1 \equiv \beta$, so that $I_e \equiv \frac{V_i}{r_e + R_E}$

From Figure 6.55, to determine $Z_0$, $V_i$ is set to zero and then

$Z_0 = R_E \parallel r_e$

Figure 6.55 Defining the output impedance for the emitter-follower configuration. [7]
To find voltage gain \( (A_v) \):

Using voltage-division: \( V_o = \frac{R_B V_i}{R_B + r_e} \)

and \( A_v = \frac{V_o}{V_i} = \frac{R_B}{R_B + r_e} \)

Since \( R_B \) is usually much greater than \( r_e \), \( R_B + r_e \approx R_B \) and

\( A_v = \frac{V_o}{V_i} \approx 1 \)

Phase relationship: \( V_o \) and \( V_i \) are in phase for the emitter-follower configuration.

Example 6: For the network of Figure 6.56. Determine \( r_e \), \( Z_i \), \( Z_o \) and \( A_v \).

![Figure 6.56 For Example 6. [7]](image)

Solution:

Step 1: DC analysis

\[ V_{CC} = I_B R_B - V_{BE} - I_E R_E \]

\[ = I_B R_B - V_{BE} - (\beta_{DC} + 1) I_E R_E \]
The common-base amplifier

The common-base configuration is characterized as having a relatively low input and a high output impedance and a current gain less than 1. The voltage gain, however, can be quite large. The standard configuration appears in Figure 6.57, with the common-base $r_e$ equivalent model substituted in Figure 6.58.

\[
\begin{align*}
I_B &= \frac{V_{CC} - V_{BE}}{R_E + (\beta_{DC} + 1)R_E} \\
&= \frac{12 \text{ V} - 0.7 \text{ V}}{220 \text{k}\Omega + (101)3.3 \text{k}\Omega} = 20.42 \mu\text{A} \\
I_E &= (\beta + 1)I_B \\
&= (101)(20.42 \mu\text{A}) = 2.062 \text{ mA}
\end{align*}
\]

**Step 2: AC analysis**

\[
\begin{align*}
r_e &= \frac{26 \text{ mV}}{I_E} = \frac{26 \text{ mV}}{2.062 \text{ mA}} = 12.61 \text{ } \Omega \\
Z_b &= \beta r_e + (\beta + 1)R_E = (100)(12.61 \text{ } \Omega) + (101)(3.3 \text{ k}\Omega) = 334.56 \text{ k}\Omega \\
Z_i &= R_E \parallel Z_B = 220 \text{ k}\Omega \parallel 334.56 \text{ k}\Omega = 132.72 \text{ k}\Omega \\
Z_o &= R_E \parallel r_e = 3.3 \text{ k}\Omega \parallel 12.61 \text{ } \Omega = 12.56 \text{ } \Omega \\
A_v &= \frac{V_o}{V_i} = \frac{R_E}{R_E + r_e} = \frac{3.3 \text{ k}\Omega}{3.3 \text{ k}\Omega + 12.51 \text{ } \Omega} = 0.996 \approx 1
\end{align*}
\]

6.10 The Common-Base amplifier [7]

The common-base configuration is characterized as having a relatively low input and a high output impedance and a current gain less than 1. The voltage gain, however, can be quite large. The standard configuration appears in Figure 6.57, with the common-base $r_e$ equivalent model substituted in Figure 6.58.

![Common-base configuration](image)
To find $Z_i$:

The input impedance is $Z_i = R_E \parallel r_e$

To find $Z_o$:

The output impedance is $Z_o = R_C$

To find voltage gain $(A_v)$:

$$V_o = -I_o R_C = -(-I_e)R_C = \alpha I_e R_C$$

with $I_e = \frac{V_i}{r_e}$, so that $V_o = \alpha \left( \frac{V_i}{r_e} \right) R_C$

and $A_v = \frac{V_o}{V_i} = \frac{\alpha R_C}{r_e} \approx \frac{R_C}{r_e}$

Therefore, $V_o$ and $V_i$ are in phase for this configuration.

To find current gain $(A_i)$:

Assuming $R_B \gg r_e$ yields $I_e \approx I_i$ and $I_o = -\alpha I_e \approx -\alpha I_i$

with $A_i = \frac{I_o}{I_i} = -\alpha \approx -1$

Therefore, $I_o$ and $I_i$ are 180° out of phase for this configuration.
**Example 7:** For the network of Figure 6.59. Determine \( r_e, Z_i, Z_o, A_v \) and \( A_i \).

![Figure 6.59 For Example 7. [7]](image)

**Solution:**

**Step 1: DC analysis**

As this transistor is p-n-p transistor,

\[
I_E = \frac{V_{BB} - V_{EE}}{R_E} = \frac{2\,\text{V} - 0.7\,\text{V}}{1\,\text{k}\Omega} = 1.3\,\text{mA}
\]

**Step 2: AC analysis**

\[
r_e = \frac{26\,\text{mV}}{1.3\,\text{mA}} = \frac{26\,\text{mV}}{1.3\,\text{mA}} = 20\,\Omega
\]

\[
Z_i = R_E \parallel r_e = 1\,\text{k}\Omega \parallel 20\,\Omega = 20\,\Omega
\]

\[
= 19.61\Omega \approx r_e
\]

\[
Z_o = R_C = 5\,\text{k}\Omega
\]

\[
A_v = \frac{\alpha R_C}{r_e} = \frac{0.98 \times 5\,\text{k}\Omega}{20\,\Omega} = 24.5
\]

\[
A_i = -0.98 \approx -1
\]
6.11 Cascade Systems [7]

Two or more amplifiers can be connected in a cascaded arrangement with the output of one amplifier driving the input of the next. Each amplifier in a cascaded arrangement is known as a stage. The basic purpose of a multistage arrangement is to increase the overall voltage gain. The cascaded system is shown in Figure 6.60.

![Figure 6.60 cascaded system [7]](image)

Here, the overall voltage gain, $A_{VT}$, of cascaded amplifiers is the product of the individual voltage gains.

$$A_{VT} = A_{V1} A_{V2} A_{V3} \cdots A_{Vn}$$

where $n$ is the number of stages.

**Voltage Gain Expressed in Decibels:**

Amplifier voltage gain is often expressed in **decibels** (dB) as follows:

$$A_{\nu(dB)} = 20 \log A_{\nu}$$

This is useful in multistage systems because the overall voltage gain in dB is the sum of the individual voltage gains in dB.

$$A_{VT(dB)} = A_{V1(dB)} + A_{V2(dB)} + A_{V3(dB)} + \cdots + A_{Vn(dB)}$$
Example 8: A certain cascaded amplifier arrangement has the following voltage gains: $A_{v1} = 10$, $A_{v2} = 15$, and $A_{v3} = 20$. What is the overall voltage gain? Also express each gain in decibels (dB) and determine the total voltage gain in dB.

Solution:

\[
A_{v_f} = A_{v1}A_{v2}A_{v3} = (10)(15)(20) = 3000 \\
A_{v1}(dB) = 20\log 10 = 20.0 \, dB \\
A_{v2}(dB) = 20\log 15 = 13.5 \, dB \\
A_{v3}(dB) = 20\log 20 = 26.0 \, dB \\
A_{v_f} (dB) = A_{v1}(dB) + A_{v2}(dB) + A_{v3}(dB) = 20.0 \, dB + 13.5 \, dB + 26.0 \, dB = 69.5 \, dB
\]

6.12 Multistage Amplifier Analysis [5], [7]

We will use the two-stage capacitively coupled amplifier in Figure 6.61. Notice that both stages are identical common-emitter amplifiers with the output of the first stage capacitively coupled to the input of the second stage. Capacitive coupling prevents the dc bias of one stage from affecting that of the other but allows the ac signal to pass without attenuation because $X_C \approx 0 \, \Omega$ at the frequency of operation. Notice, also, that the transistors are labeled $Q_1$ and $Q_2$.

Loading Effects: In determining the voltage gain of the first stage, you must consider the loading effect of the second stage. Because the coupling capacitor $C_3$ effectively appears as a short at the signal frequency, the total input resistance of the second stage presents an ac load to the first stage.

Looking from the collector of $Q_1$, the two biasing resistors in the second stage, $R_5$ and $R_6$, appear in parallel with the input resistance at the base of $Q_2$. In other words, the signal at the collector of $Q_1$ “sees” $R_3$, $R_5$, $R_6$, and $Z_b$ (2nd stage) of the second stage all in parallel to ac ground. Thus, the effective ac collector resistance of $Q_1$ is the total of all these resistances in parallel, as Figure 6.62 and 6.63 illustrate.
Figure 6.61 A two-stage common-emitter amplifier. [5]

Figure 6.62 AC equivalent circuit of the two-stage common-emitter amplifier.
Voltage Gain of the First Stage:

From Figure 6.63, the ac collector resistance of the first stage is

\[ R_{c1} = R_3 \parallel R_5 \parallel R_6 \parallel \beta r_e(2^{nd} \text{ stage}) \]

Here, for both stages: \( I_E = 1.05 \text{ mA}, \ r_e = 23.8 \ \Omega, \ \text{and} \ \beta r_e(2^{nd} \text{ stage}) = 3.57 \ \text{k} \Omega. \)

Therefore the effective ac collector resistance of the first stage is

\[ R_{c1} = 4.7 \ \text{k} \Omega \parallel 47 \ \text{k} \Omega \parallel 10 \ \text{k} \Omega \parallel 3.57 \ \text{k} \Omega = 1.63 \ \text{k} \Omega \]

Therefore the base-to-collector voltage gain of the first stage is

\[ A_{v1} = -\frac{R_{c1}}{r'_e} = -\frac{1.63 \ \text{k} \Omega}{23.8 \ \Omega} = -68.5 \]

Voltage Gain of the Second Stage:

From Figure 6.64, the second stage has no load resistor, so the ac collector resistance is \( R_7 \), and the gain is

\[ A_{v2} = -\frac{R_7}{r'_e} = -\frac{4.7 \ \text{k} \Omega}{23.8 \ \Omega} = -197 \]
Figure 6.64 AC equivalent circuit of 2nd stage common-emitter amplifier.

**Overall Voltage Gain:**

The overall amplifier gain with no load on the output is

\[ A_{vT} = A_{v1} A_{v2} = (-68.5)(-197) \approx 13,495 \]

The overall voltage gain can be expressed in dB as follows:

\[ A_{vT}(dB) = 20\log(13,495) = 82.6 \text{ dB} \]

**DC Voltage in the Capacitively Coupled Multistage Amplifier:**

Since both stages are identical and \( R_1 = R_5, \ R_2 = R_6, \ R_3 = R_7, \) and \( R_4 = R_8, \) therefore the dc voltages for \( Q_1 \) and \( Q_2 \) are the same.

**Example 9:**

For the two-stage common emitter amplifier shown in Figure 6.65.

(a) Determine the voltage gain \( (A_v) \) of each stage.

(b) Determine the overall voltage gain \( (A_{vT}) \) of this multistage amplifier.

(c) Draw the waveform of output voltage \( (V_{out}) \).
Solution:

(a) Step 1: DC Analysis:

Figure 6.66 For Example 9.
As $R_1 = R_5$, $R_2 = R_6$, $R_3 = R_7$, and $R_4 = R_8$, therefore the dc voltages for $Q_1$ and $Q_2$ are the same.

**Step 2: AC analysis:**

\[
\begin{align*}
\beta r_e(1^{\text{st}} \text{ stage}) &= \beta r_e(2^{\text{nd}} \text{ stage}) = \beta_{ac} r_e \\
r_e &= \frac{26 \text{ mV}}{I_E} = \frac{26 \text{ mV}}{2.203 \text{ mA}} = 11.802 \text{ k}\Omega \\
\therefore \beta_{ac} r_e &= 175 \times 11.802 \text{ k}\Omega = 2.065 \text{ k}\Omega
\end{align*}
\]

For 1\textsuperscript{st} state

![Diagram of a circuit with labels and symbols: $\beta r_e(2^{\text{nd}} \text{ stage}) = \beta_{ac} r_e$, $R_{c1}$, 50 $\mu$Vrms, R1, R2, 33 k$\Omega$, 8.2 k$\Omega$, R3, R5, R6, 33 k$\Omega$, 33 k$\Omega$, 8.2 k$\Omega$.]

Figure 6.67 For Example 9.
\[ R_{cl} = R_3 // R_5 // R_6 // \beta r_e(2^{nd \ \text{stage}}) = 3.3 // 33 // 8.2 // 2.065 = 1.064 \, \text{k}\Omega \]

\[ \therefore A_{v1} = -\frac{R_{c1}}{r_e} = -\frac{1.064 \, \text{k}\Omega}{11.802 \, \Omega} = -90.154 \]

For 2\text{nd state}

\[ R_{c2} = R_7 // R_L = 3.3 // 18 = 2.789 \, \text{k}\Omega \]

\[ \therefore A_{v2} = -\frac{R_{c2}}{r_e} = -\frac{2.789 \, \text{k}\Omega}{11802 \, \Omega} = -236.316 \]

(b) \[ A_{vT} = A_{v1} A_{v2} = (-90.154)(-236.316) \approx 21305 \]

(c) \[ \frac{V_{out}}{V_{in}} = A_{vT} \]

\[ V_{out} = A_{vT} \times V_{in} = 21305 \times 50 \mu V_{rms} \]

\[ = 1.065 \, V_{rms} = 1.065 \times \sqrt{2} = 1.506 \, V(p) \]
Example 10:

a. Calculate the overall voltage gain \((A_{VT})\) and output voltage of the RC-coupled transistor amplifiers.

b. Calculate the input impedance of the first stage and the output impedance of the second stage.
Solution:

(a) The dc bias analysis results in the following for each transistor:

\[ V_B = 4.7V, V_E = 4.0V, V_C = 11V, I_E = 4.0mA \]

\[ r_e = \frac{26mV}{I_E} = \frac{26mV}{4mA} = 6.5\Omega \]

Therefore the voltage gain for the first stage becomes

\[ A_{v1} = -\frac{R_{c1}}{r_e} = -\frac{R_4 \| (R_5 \| R_6 \| \beta r_e)}{r_e} \]

\[ = - \frac{(2.2k\Omega \| (15k\Omega \| 4.7k\Omega \| 200)(6.5\Omega))}{6.5\Omega} \]

\[ = - \frac{665.2\Omega}{6.5\Omega} = -102.3 \]

For the uploaded second stage gain is

\[ A_{v2} = -\frac{R_7}{r_e} = -\frac{2.2k\Omega}{6.5\Omega} = -338.46 \]

Result in an overall gain of

\[ A_{v_r} = A_{v1}A_{v2} = (-102.3)(-338.46) = 34,624.46 \]

The output voltage is then

\[ V_o = A_{v_r} V_i = (34.6 \times 10^3)(25\mu V) \approx 865mV \]
(b) The input impedance of the first stage is

\[ Z_{i1} = R_1 || R_2 \| \beta r_e = 4.7k\Omega || 15k\Omega || (200)(6.5\Omega) = 953.6\Omega \]

Whereas the output impedance for the second stage is

\[ Z_{o2} = R_C = R_7 = 2.2k\Omega \]

And \( Z_{o2} \) becomes the output impedance for the multi-stage amplifier, therefore

\[ Z_{o2} = Z_o = 2.2k\Omega \]

6.13 Homework 10

1. Consider this two-stage common emitter amplifier.

(a) Determine the voltage gain \( (A_v) \) of each stage.

(b) Determine the overall voltage gain \( (A_{vT}) \) of this multistage amplifier.

(c) Draw the waveform of output voltage \( (V_{out}) \).

\[ \beta_{DC} = \beta_{ac} = 150 \]

\[ +20 \text{ V} \]

\[ \text{R}_1 30\, \text{k}\Omega \]
\[ \text{R}_3 3\, \text{k}\Omega \]
\[ \text{R}_5 20\, \text{k}\Omega \]
\[ \text{R}_7 5\, \text{k}\Omega \]
\[ \text{R}_2 6\, \text{k}\Omega \]
\[ \text{R}_4 1\, \text{k}\Omega \]
\[ \text{R}_6 5\, \text{k}\Omega \]
\[ \text{R}_8 1\, \text{k}\Omega \]

\[ \text{V}_{in} \]
\[ \sim 100\, \text{mV}_p \]

\[ \text{R}_1 30\, \text{k}\Omega \]
\[ \text{R}_3 3\, \text{k}\Omega \]
\[ \text{R}_5 20\, \text{k}\Omega \]
\[ \text{R}_7 5\, \text{k}\Omega \]
\[ \text{R}_2 6\, \text{k}\Omega \]
\[ \text{R}_4 1\, \text{k}\Omega \]
\[ \text{R}_6 5\, \text{k}\Omega \]
\[ \text{R}_8 1\, \text{k}\Omega \]

\[ \text{V}_{out} \]
\[ +20 \text{ V} \]

\[ \text{R}_1 20\, \text{k}\Omega \]

\[ \text{V}_{out} \]

Figure 6.71 For problem 1.
2. Consider this two-stage common emitter amplifier. Assume $\beta_{DC} = \beta_{ac} = 100$

(a) Determine the voltage gain ($A_v$) of each stage.

(b) Determine the overall voltage gain ($A_{VT}$) of this multistage amplifier.

(c) Express $A_{VT}$ in decibels (dB).

3. For the two-stage, capacitively coupled amplifier in Figure 6.73, find the following values:

   (a) voltage gain ($A_v$) of each stage.

   (b) overall voltage gain ($A_{VT}$) of this amplifier.

   (c) Express the gains found in (a) and (b) in decibels (dB).
4. If the multistage amplifier in the figure of problem 3 is driven by a $75 \, \Omega$, $50 \, \mu$V source and the second stage is loaded with an $R_L = 18 \, k\Omega$, determine:

(a) voltage gain ($A_v$) of each stage.

(b) overall voltage gain ($A_{VT}$) of this amplifier.

(c) Express the gains found in (a) and (b) in decibels (dB).

5. Figure 6.74 shows a two-stage common emitter amplifier.

(a) Determine the voltage gain ($A_v$) of each stage. Using $I_E = I_B + I_C$.

(b) Determine the overall voltage gain ($A_{VT}$) of this multistage amplifier.

(c) Determine the $Z_{in}$ and $Z_{out}$ of this multistage amplifier.
6. Figure 6.75 shows a two-stage common emitter amplifier.

   (a) Determine the voltage gain ($A_v$) of each stage. Using $I_E \approx I_C$.

   (b) Determine the overall voltage gain ($A_{VT}$) of this multistage amplifier.

   (c) Determine the $Z_{in}$ and $Z_{out}$ of this multistage amplifier.
\beta_{DC} = \beta_{ac} = 150

Figure 6.75 For problem 6.