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BJT Small Signal Analysis

• $r_e$ transistor model – employs a diode and controlled current source to duplicate the behavior of a transistor in the region of interest.

• The $r_e$ and hybrid models will be used to analyze small-signal AC analysis of standard transistor network configurations.

  Ex: Common-base, common-emitter and common-collector configurations.

• The network analyzed represent the majority of those appearing in practice today.

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AC equivalent of a network is obtained by:

1. Setting all DC sources to zero
2. Replacing all capacitors by s/c equiv.
3. Redraw the network in more convenient and logical form
Transistor circuit under examination in this introductory discussion.

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The network of Fig. 5.3 following removal of the dc supply and insertion of the short-circuit equivalent for the capacitors.

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Circuit of Fig. 5.4 redrawn for small-signal ac analysis.
The input ($V_i$) is applied to the base and the output ($V_o$) is from the collector.

The Common-Emitter is characterized as having high input impedance and low output impedance with a high voltage and current gain.
Common-Emitter (CE) Fixed-Bias Configuration

Removing DC effects of $V_{cc}$ and Capacitors

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**Common-Emitter (CE) Fixed-Bias Configuration**

**re Model**

Determine $\beta$, $r_e$, and $r_o$:

$\beta$ and $r_o$: look in the specification sheet for the transistor or test the transistor using a curve tracer.

$r_e$: calculate $r_e$ using dc analysis:

$$r_e = \frac{26mV}{I_S}$$

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Impedance Calculations

Common-Emitter (CE) Fixed-Bias Configuration

Input Impedance:

\[ Z_i = R_B \parallel \beta r_e \]

\[ Z_i \approx \beta r_e \quad \text{if} \quad R_B \geq 10 \beta r_e \]

Output Impedance:

\[ Z_o = R_C \parallel r_o \]

\[ Z_o \approx R_c \quad \text{if} \quad r_o \geq 10 R_c \]

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Gain Calculations

Voltage Gain ($A_v$):

$$A_v = \frac{V_o}{V_i} = - \frac{(R_C \parallel r_o)}{r_e}$$

$$A_v = -\frac{R_C}{r_e} / r_o \geq 10R_C$$

Current Gain ($A_i$):

$$A_i = \frac{I_o}{I_i} = \frac{\beta R_B r_o}{(r_o + R_C)(R_B + \beta r_e)}$$

$$A_i \approx \beta / r_o \geq 10R_C, R_B \geq 10\beta r_e$$

Current Gain from Voltage Gain:

$$A_i = -A_v \frac{Z_i}{R_C}$$

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Common-Emitter (CE) Fixed-Bias Configuration

Voltage Gain

\[ A_v = \frac{V_o}{V_i} \]

\[ V_o = -\beta I_b (R_C \parallel r_o) \]

\[ V_i = I_b \beta r_e \]

\[ A_v = \frac{-\beta I_b (R_C \parallel r_o)}{I_b \beta r_e} \]

\[ = \frac{(R_C \parallel r_o)}{r_e} \]

if \( r_o = \infty \Omega \) or \( \geq 10R_C \)

\[ A_v = \frac{R_C}{r_e} \]

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Current gain

The current gain is determined by applying the current-divider rule to the input and output circuits

\[ I_o = \frac{r_o \beta I_b}{r_o + R_C} \text{ and } I_o = \frac{r_o \beta}{I_b} \frac{1}{r_o + R_C} \]

\[ I_b = \frac{R_B I_i}{R_B + \beta r_e} \text{ and } I_b = \frac{R_B}{I_i} \frac{1}{R_B + \beta r_e} \]

\[ A_i = \frac{I_o}{I_i} = \left( \frac{I_o}{I_b} \right) \left( \frac{I_b}{I_i} \right) = \left( \frac{r_o \beta}{r_o + R_C} \right) \left( \frac{R_B}{R_B + \beta r_e} \right) \]

\[ \therefore A_i = \frac{I_o}{I_i} = \frac{r_o \beta R_B}{(r_o + R_C)(R_B + \beta r_e)} \]

if \( r_o \geq 10R_C \) and \( R_B \geq 10\beta r_e \),

\[ \therefore A_i = \frac{I_o}{I_i} \approx \frac{r_o \beta R_B}{(r_o)(R_B)} = \beta \]

or we can use this equation too

\[ \therefore A_i = -A_v \frac{Z_i}{R_C} \]

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The phase relationship between input and output is 180 degrees. The negative sign used in the voltage gain formulas indicates the inversion.
CE – Voltage-Divider Bias Configuration

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You still need to determine $\beta$, $re$, and $ro$.

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Impedance Calculations

### Input Impedance:

\[
R' = R_1 \parallel R_2 = \frac{R_1 R_2}{R_1 + R_2}
\]

\[
Z_{i} = R' \parallel B r_{e}
\]

### Output Impedance:

\[
Z_{o} \approx R_c \parallel r_o
\]

\[
Z_{o} \approx R_c / r_o \geq 10R_c
\]

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Gain Calculations

Voltage Gain (Av):

\[ A_v = \frac{V_o}{V_i} = -\frac{R_C \parallel r_o}{r_e} \]

\[ A_v = \frac{V_o}{V_i} \approx -\frac{R_C}{r_e} \quad \text{if} \quad r_o \geq 10R_C \]

Current Gain (Ai):

\[ A_i = \frac{I_o}{I_i} = \frac{\beta R' r_o}{(r_o + R_C)(R' + \beta r_e)} \]

\[ A_i = \frac{I_o}{I_i} \approx \frac{\beta R'}{R' + \beta r_e} \quad \text{if} \quad r_o \geq 10R_C \]

Current Gain from Voltage Gain:

\[ A_i = \frac{I_o}{I_i} \approx \beta \quad \text{if} \quad r_o \geq 10R_C, R' \geq 10\beta r_e \]

\[ A_i = -A_v \frac{Z_i}{R_C} \]

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Voltage Gain

\[ V_O = - (\beta I_b)(R_C \parallel r_o) \]

\[ I_b = \frac{V_i}{\beta r_e} \]

\[ V_o = -\beta \left( \frac{V_i}{\beta r_e} \right)(R_C \parallel r_o) \]

\[ \therefore A_v = \frac{-(R_C \parallel r_o)}{r_e} \]

if \( r_o = \infty \Omega \) or \( \geq 10R_C \) \( \therefore A_v = \frac{-R_C}{r_e} \)
Current gain

since the network is so similar to that common - emitter fixed - bias configuration, except for the R', the equation for the current gain will have the same format.

\[ R' = R_1 \parallel R_2 = R_B \]

\[ A_i = \frac{I_o}{I_i} = \frac{\beta R' r_o}{(r_o + R_C)(R' + \beta r_e)} \]

for \( r_o \geq 10R_C \),

\[ A_i = \frac{I_o}{I_i} \approx \frac{\beta R' r_o}{r_o(R' + \beta r_e)} \]

\[ \approx \frac{\beta R'}{(R' + \beta r_e)} \]

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And if $R' \geq 10 \beta r_e$, 

$$A_i = \frac{I_o}{I_i} = \frac{\beta R'}{R'}$$

$$\therefore A_i = \frac{I_o}{I_i} \approx \beta$$

as an option

$$\therefore A_i = -A_v \frac{Z_i}{R_C}$$
A CE amplifier configuration will always have a phase relationship between input and output is 180 degrees. This is independent of the DC bias.
CE Emitter-Bias Configuration

Unbypassed $R_E$

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Again you need to determine $\beta$, re.

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Impedance Calculations

Input Impedance:

\[ Z_b = \beta r_e + (\beta + 1)R_E \]

\[ Z_b \approx \beta (r_e + R_E) \]

\[ Z_b \approx \beta R_E \quad \text{if} \quad R_E \gg r_e \]

Output Impedance:

\[ Z_o = R_C \]

\[ Z_i = R_B \parallel Z_b \]

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Defining the input impedance of a transistor with an unbypassed emitter resistor

Applying KVL to the input side:

\[ V_i = I_b \beta r_e + I_e R_E \]

\[ V_i = I_b \beta r_e + (\beta + 1)I_b R_E \]

\[ \therefore Z_b = \frac{V_i}{I_b} = \beta r_e + (\beta + 1)R_E \]

since \( \beta \) is normally greater than 1,

\[ \therefore Z_b \approx \beta r_e + \beta R_E \]

since \( R_E \) is much greater than \( r_e \), eqn above can be reduced to

\[ \therefore Z_b \approx \beta R_E \]
Voltage Gain (Av):

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

Current Gain (Ai):

\[
A_i = \frac{I_o}{I_i} = \frac{\beta R_B}{R_B + Z_b}
\]

Current Gain from Voltage Gain:

\[
A_i = -A_v \frac{Z_i}{R_C}
\]

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CE Emitter-Bias Configuration

Voltage Gain

\[ I_b = \frac{V_i}{Z_b} \]

\[ V_o = -I_o R_C = -\beta I_b R_C \]

\[ = -\beta \left( \frac{V_i}{Z_b} \right) R_C \]

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

Substituting \( Z_b = \beta (r_e + R_E) \) gives

\[ A_v = \frac{V_o}{V_i} = -\frac{R_C}{r_e + R_E} \]

And for the approximation \( Z_b \cong \beta R_E \)

\[ A_v = \frac{V_o}{V_i} = -\frac{R_C}{R_E} \]

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CE Emitter-Bias Configuration

Current Gain

The magnitude of $R_B$ is often too close to $Z_b$ to permit the approximation $I_b = I_i$. Applying the current-divider rule to the input circuit will result in:

$$I_b = \frac{R_B I_i}{R_B + Z_b}$$

$$\frac{I_b}{I_i} = \frac{R_B}{R_B + Z_b}$$

$$I_o = \beta I_b$$

$$\frac{I_o}{I_b} = \beta$$

$$\therefore A_i = \frac{I_o}{I_i} = \frac{I_o}{I_b} \frac{I_b}{I_i} = \beta \frac{R_B}{R_B + Z_b}$$

$$\therefore A_i = -A_v \frac{Z_i}{R_c}$$

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Phase Relationship

A CE amplifier configuration will always have a phase relationship between input and output is 180 degrees. This is independent of the DC bias.

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This is the same circuit as the CE fixed-bias configuration and therefore can be solved using the same re model.
You may recognize this as the Common-Collector configuration. Indeed they are the same circuit.

Note the input is on the base and the output is from the emitter.

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You still need to determine $\beta$ and $r_e$.

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Emitter-Follower Configuration

Impedance Calculations

Input Impedance:

\[
Z_i = R_B \parallel Z_b
\]

\[
Z_b = \beta r_e + (\beta + 1)R_E
\]

\[
Z_b \approx \beta (r_e + R_E)
\]

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Calculation for the current $I_e$

$$I_b = \frac{V_i}{Z_b}$$

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

Substituting for $Z_b$ gives

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

$$= \frac{V_i}{\beta r_e / (\beta + 1) + R_E} \quad \text{but } (\beta + 1) \approx \beta$$

And $\frac{\beta r_e}{(\beta + 1)} \approx \frac{\beta r_e}{\beta} = r_e$

$$\therefore I_e = \frac{V_i}{r_e + R_E}$$

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Emittor-Follower Configuration

Impedance Calculations (cont’d)

Output Impedance:

Defining the output impedance for the emitter follower configuration

\[ I_e = \frac{V_i}{r_e + R_E} \]

\[ Z_o = R_E \parallel r_e \]

\[ Z_o \approx r_e \quad / \quad R_E \gg r_e \]

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Gain Calculations

Emitter-Follower Configuration

Voltage Gain ($A_v$):

\[ A_v = \frac{V_o}{V_i} = \frac{R_E}{R_E + r_e} \]

\[ A_v = \frac{V_o}{V_i} \approx 1 \quad / \quad R_E >> r_e, R_E + r_e \approx R_E \]

Current Gain ($A_i$):

\[ A_i \approx -\frac{\beta R_B}{R_B + Z_b} \]

Current Gain from Voltage Gain:

\[ A_i = -A_v \frac{Z_i}{R_E} \]

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Voltage gain

\[ V_o = \frac{R_E V_i}{R_E + r_e} \]

\[ \therefore A_v = \frac{V_o}{V_i} = \frac{R_E}{R_E + r_e} \]

\[ R_E \text{ usually much greater than } r_e, \]
\[ R_E + r_e \approx R_E \]

\[ \therefore A_v = \frac{V_o}{V_i} \approx 1 \]

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Emitter-Follower Configuration

**Current Gain**

\[
I_b = \frac{R_B I_i}{R_B + Z_b}
\]

\[
I_b = R_B
I_i = \frac{R_B}{R_B + Z_b}
\]

\[
I_o = -I_e = -(\beta + 1)I_b
\]

\[
\frac{I_o}{I_b} = -(\beta + 1)
\]

\[
A_i = \frac{I_o}{I_i} = \frac{I_o}{I_b} \frac{I_b}{I_i} = -(\beta + 1) \frac{R_B}{R_B + Z_b}
\]

since \((\beta + 1) \cong \beta\),

\[
\therefore A_i \cong -\frac{\beta R_B}{R_B + Z_b}
\]

or \[
A_i = -A_y \frac{Z_i}{R_E}
\]

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Emitter-Follower Configuration

Phase Relationship

A CC amplifier or Emitter Follower configuration has no phase shift between input and output.
The input ($V_i$) is applied to the emitter and the output ($V_o$) is from the collector.

The Common-Base is characterized as having low input impedance and high output impedance with a current gain less than 1 and a very high voltage gain.
You will need to determine $\alpha$ and $re$.

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Common-Base (CB) Configuration

Impedance Calculations

Input Impedance:

\[ Z_i = R_E \parallel r_e \]

Output Impedance:

\[ Z_o = R_C \]

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Common-Base (CB) Configuration

Gain Calculations

Voltage Gain ($A_v$):

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

Current Gain ($A_i$):

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

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Common-Base (CB) Configuration

Voltage & Current gain

\[ V_o = -I_o R_C = -(-I_c R_C) \]
\[ = \alpha I_e R_C \]
\[ I_e = \frac{V_i}{r_e} \]
\[ V_o = \alpha \left( \frac{V_i}{r_e} \right) R_C \]
\[ \therefore A_v = \frac{V_o}{V_i} = \alpha \frac{R_C}{r_e} \approx \frac{R_C}{r_e} \]

\[ I_e = I_i \]
\[ I_o = -\alpha I_e = -\alpha I_i \]
\[ \therefore A_i = \frac{I_o}{I_i} = -\alpha = -1 \]
Common-Base (CB) Configuration

Phase Relationship

A CB amplifier configuration has no phase shift between input and output.

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The network has a dc feedback resistor for increased stability, yet the capacitor $C_3$ will shift portions of the feedback resistance to the input and output sections of the network in the ac domain. The portion of $R_F$ shifted to the input or output side will be determined by the desired ac input and output resistance levels.
Substituting the $re$ equivalent circuit into the ac equivalent network

**Input Impedance:**

\[ Z_i = R_{F1} \parallel \beta r_e \]

**Output Impedance:**

\[ Z_o = R_C \parallel R_{F2} \parallel r_o \]

\[ Z_o \cong R_C \parallel R_{F2} \]

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Collector DC Feedback Configuration

Voltage Gain

\[ R' = r_o \parallel R_{F2} \parallel R_C \]

\[ V_o = -\beta I_b R' \]

\[ I_b = \frac{V_i}{\beta r_e} \]

\[ V_o = -\beta \frac{V_i}{\beta r_e} R' \]

\[ \therefore A_v = \frac{V_o}{V_i} = -\frac{r_o \parallel R_{F2} \parallel R_C}{r_e} \]

for \( r_o \geq 10R_C \),

\[ \therefore A_v = \frac{V_o}{V_i} = -\frac{R_{F2} \parallel R_C}{r_e} \]

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Collector DC Feedback Configuration

For the input side \( \text{Current Gain} \)

\[
I_b = \frac{R_F I_i}{R_F + \beta r_e} \quad \text{or} \quad \frac{I_b}{I_i} = \frac{R_F}{R_F + \beta r_e}
\]

and for the output side using \( R' = r_o \parallel R_{F2} \)

\[
I_o = \frac{R' \beta I_b}{R' + R_C} \quad \text{or} \quad \frac{I_o}{I_b} = \frac{R' \beta}{R' + R_C}
\]

the current gain ,

\[
A_i = \frac{I_o}{I_i} = \frac{I_o}{I_b} \cdot \frac{I_b}{I_i} = \frac{R' \beta}{R' + R_C} \cdot \frac{R_{F1}}{R_F + \beta r_e}
\]

\[
\therefore A_i = \frac{I_o}{I_i} \approx \frac{R' \beta R_{F1}}{(R' + R_C)(R_{F1} + \beta r_e)}
\]

since \( R_{F1} \) is usually much larger than \( \beta r_e \), \( R_{F1} + \beta r_e \approx R_{F1} \)

\[
A_i = \frac{I_o}{I_i} \approx \frac{\beta R_{F1} (r_o \parallel R_{F2})}{R_{F1} (r_o \parallel R_{F2} + R_C)}
\]

\[
\therefore A_i = \frac{I_o}{I_i} \approx \frac{\beta}{1 + \frac{R_C}{r_o \parallel R_{F2}}}
\]

or \( \therefore A_i = \frac{I_o}{I_i} = -A_v \frac{Z_i}{R_C} \)

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Approximate Hybrid Equivalent Circuit

The h-parameters can be derived from the re model:

\[ h_{ie} = \beta r_e \quad h_{ib} = r_e \]
\[ h_{fe} = \beta \quad h_{fb} = -\alpha \]
\[ h_{oe} = 1/ro \]

The h-parameters are also found in the specification sheet for the transistor.
Approximate Common-Emitter Equivalent Circuit

Hybrid equivalent model

re equivalent model

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Approximate Common-Base Equivalent Circuit

Hybrid equivalent model

re equivalent model

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Troubleshooting

1. **Check the DC bias voltages** – if not correct check power supply, resistors, transistor. Also check to ensure that the coupling capacitor between amplifier stages is OK.

2. **Check the AC voltages** – if not correct check transistor, capacitors and the loading effect of the next stage.
Practical Applications

• Audio Mixer

• Preamplifier

• Random-Noise Generator

• Sound Modulated Light Source