Large Signal Amplifier

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Objective

• To investigate the design and operation of a large-signal bipolar transistor power amplifier for operation in the audio frequency range.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power Supply</td>
<td>±24 V</td>
</tr>
<tr>
<td>Output Signal Power</td>
<td>10 W</td>
</tr>
<tr>
<td>Bandwidth</td>
<td>&gt;10 KHz</td>
</tr>
<tr>
<td>Input Impedance</td>
<td>&gt;1 KΩ</td>
</tr>
<tr>
<td>Load Impedance</td>
<td>16 Ω</td>
</tr>
<tr>
<td>Input Signal Level</td>
<td>50 mV</td>
</tr>
</tbody>
</table>
Method - Three Stages

1. Differential Amplifier
   – Voltage Amplification
   – Output is amplified difference between input and sampled output via connected feedback resistor.

2. Common Emitter Amplifier
   – Voltage amplification

3. Power Stage
   – Current amplification = allows high power at load
Hybrid Pi BJT Model

• Linearized small signal model.
• Low frequency.

Input resistance into base:

Transconductance:

Currents:

Actually depends on $V_{CE}$:

(Early Affect)

Relationship to Beta:

\[ i_c = g_m V_{be} = g_m (i_b r_\pi) = \beta i_b \Rightarrow \beta = \frac{i_c}{i_b} \]
BJT T Model

From previous slide: \[ g_m = \frac{I_C}{V_T} \]

Currents:
\[ i_C = g_m V_{be} \quad i_e = \frac{V_{be}}{r_e} \]
\[ i_b = i_e - i_c = \frac{V_{be}}{(1 + \beta)r_e} \]

Comparing to pi model:
\[ i_{b,\pi} = i_{b,T} \Rightarrow \frac{V_{be}}{(1 + \beta)r_e} = \frac{V_{be}}{r_\pi} \Rightarrow r_\pi = (1 + \beta)r_e \]

Solving for collector current:
\[ i_c = g_m V_{be} = g_m(i_e r_e) = \alpha i_e \Rightarrow \alpha = \frac{i_c}{i_e} \]
Current Mirror

• Current through Q1 sets up \( V_{BE} \) across Q1. Also across Q2.
• If Q1 matches Q2, \( I_{OUT} = I_{REF} \) (Ideally)
• Necessary for Q2 to be “on” \( (V_{CE}) \).

\[
I_{REF} = I_C + \frac{2I_C}{\beta} = I_C \left(1 + \frac{2}{\beta}\right)
\]

\[
\frac{I_{OUT}}{I_{REF}} = \frac{I_C}{I_C \left(1 + \frac{2}{\beta}\right)} = \frac{1}{\left(1 + \frac{2}{\beta}\right)}
\]
Transistor Differential Amplifier

- High differential voltage gain
- Common Mode Rejection (transistor parameters similar)
- Provides initial voltage amplification
- Very handy to connect feedback resistor from output here (amplify difference of output sampled and input).
BJT Differential Amplifier

- Emitters connected together
- Two bases as inputs
- Collectors have differential amplified output
- But why...
BJT Differential Amplifier

- Think:
  - Transistor on left is common emitter.
  - Transistor on right is emitter follower.
- Transistor on right “feeds” input voltage (base voltage) to emitter of left transistor.
- Since left transistor amplifies current between base and emitter, the collector current is proportional to the difference between inputs.
- Replace emitter resistor with current mirror as constant current source – constant current with varying common mode!
BJT Differential Amplifier - Gain

From hybrid-pi model, collector current:

\[ i_C = g_m V_{be} \quad \quad g_m = \frac{I_C}{V_T} \]

Collector Voltage:

\[ V_C = R_C i_C \quad \quad V_C = R_C g_m V_{be} \]

Since right side grounded, all input at left transistor base:

\[ V_{be} = V_i \quad \quad V_{c1} = V_o \]

One output has half voltage amplification:

\[ V_o = \frac{R_C g_m V_i}{2} \]

Voltage gain:

\[ A_V = \frac{V_o}{V_i} = -\frac{g_m R_C}{2} \]

Relies on nearly equal Betas and ideal current source (common mode has no effect)!
BJT Differential Amplifier – Input Resistance

From T Model slide:

\[ i_b = \frac{i_e}{(1 + \beta)} \]

Solving current through both transistors:

\[ i_e = \frac{V_{be}}{2r_e} \quad V_{be} = V_i \quad \rightarrow \quad i_b = \frac{V_i}{2(1 + \beta) r_e} \]

Using:

\[ r_\pi = (1 + \beta) r_e \]

Input Resistance:

\[ R_i = \frac{V_i}{i_b} = 2(1 + \beta) r_e = 2r_\pi \]
Differential Amplifier – Results

- Inverted output.
- High voltage gain.

<table>
<thead>
<tr>
<th></th>
<th>Gain</th>
</tr>
</thead>
<tbody>
<tr>
<td>Calculated</td>
<td>-52.8 V/V</td>
</tr>
<tr>
<td>Measured</td>
<td>-36.63 V/V</td>
</tr>
</tbody>
</table>

- Smaller bias current in final design, leads to smaller gain.
BJT Common Emitter Amplifier

- High Voltage Gain
- Inverted Output
- Using transistor alone, gain relies heavily on temperature.
- \( R_E \) provides negative feedback.
Common Emitter – T Model

Input resistance:

\[ R_i = \frac{V_i}{i_b} = \frac{V_i}{\frac{V_i}{(1 + \beta)(r_e + R_E)}} = (1 + \beta)(r_e + R_E) \]

Voltage Gain:

\[ v_o = -i_c(R_C || R_L) = -\alpha i_e(R_C || R_L) \]

\[ i_e = \frac{v_i}{r_e + R_E} \]

\[ A_v = \frac{v_o}{v_i} = -\frac{R_C || R_L}{r_e + R_E} \]
CE Amplifier - Results

- Very similar to expected gain.
- Inverted output.

<table>
<thead>
<tr>
<th></th>
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</tr>
</thead>
<tbody>
<tr>
<td>Calculated</td>
<td>-50.7 V/V</td>
</tr>
<tr>
<td>Measured</td>
<td>-45.6 V/V</td>
</tr>
</tbody>
</table>
Power Stage Design Choices

Class A – 100% conduction

- Transistor maintains conduction even when no input signal applied
- Virtually no distortion (operated in linear range), but lower efficiency.
- Typically biased in middle of linear region.
- Inverting

Class B – 50% conduction

- One transistor “on” at a time = no quiescent current.
- Higher efficiency, has distortion...
- Non-inverting
Class B Push-Pull Amplifier

- Complementary pair of BJTs.
- Operate as Emitter Followers
- NPN “on” during positive input (above ~.7V)
- Transistors alternately conduct (for sine input, each on half time ideally)
  - This is push-pull behavior!
Crossover Distortion

- In class B amplifier, around input of 0V, both transistors are off.
- \(\approx +0.7V\) needed to turn NPN “on”
- \(\approx -0.7V\) needed to turn PNP “on”
- Causes distortion seen in output above.
Solution - Class AB Push-Pull Amplifier

- Both transistors are nearly “on” at the 0V point (just below $V_{BE} \approx 0.7V$).
- More power dissipation than Class B circuit, less than Class A, and no crossover distortion.
Overcurrent Protection

- Too much current through power transistor?
- Voltage across $R_E$ turns on auxiliary transistor, “shunting” excess base current to load.
- $\approx 1.49A$ turns on auxiliary with $0.47 \ \Omega \ R_E$.
- Input “sees” more of load, so input voltage sags (effectively “lowers” power transistor Beta)
- $R_E$ also helps protect against thermal drift!
Replace Diodes with Transistor

- When voltage across RaPOT is $\approx 0.7V$, transistor Q9 turns on.
- Creates equilibrium that maintains $V_{BE}$ of $\approx 0.7V$.
- Use potentiometer to adjust for $V_{CB} \approx 0.7V$ as well.
- Same effect as two diodes!
Power Amplifier – Lab Results

- Non-inverting
- Near unity voltage gain.

<table>
<thead>
<tr>
<th></th>
<th>Gain</th>
</tr>
</thead>
<tbody>
<tr>
<td>Calculated</td>
<td>1 V/V</td>
</tr>
<tr>
<td>Measured</td>
<td>.97 V/V</td>
</tr>
</tbody>
</table>

- No voltage gain, but by allowing for additional output current, effectively lowers output resistance.
1. Differential Amplifier
   – Voltage Amplification
   – Output is difference between input and sampled output (feedback!)

2. Common Emitter Amplifier
   – Voltage amplification

3. Power Stage
   – Current amplification = allows high power at load

No feedback yet...
AC Coupled

- Capacitance between differential amp and CE amp.
- Bias network still attached to CE amp (loading DA).

$$A_1 = \text{Differential Amplifier Gain}$$
$$A_2 = \text{CE Amp Gain} + \text{Power Stage Gain}$$

**OL AC Coupled Gain:**

$$G_{OL\_AC} = A_1 A_2 \times K$$

$$K = \frac{R_{Bias} \parallel R_C}{R_C}$$
AC Coupled - Results

- Real values for two voltage gain stages used in this calculation.
- Two inverting stages cause overall non-inverting amplifier.

<table>
<thead>
<tr>
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<tbody>
<tr>
<td>Calculated</td>
<td>71.8 V/V</td>
</tr>
<tr>
<td>Measured</td>
<td>71.4 V/V</td>
</tr>
</tbody>
</table>
DC Coupled

- Capacitance removed, bias network removed.
- Now CE amp receiving bias voltage from differential amplifier circuit.
- Leads to much higher gain:

\[ G_{OL_{-DC}} = A_1 A_2 \]

Still no feedback...
DC Coupled, Open Loop Results

<table>
<thead>
<tr>
<th></th>
<th>Gain</th>
</tr>
</thead>
<tbody>
<tr>
<td>Calculated</td>
<td>1667 V/V</td>
</tr>
<tr>
<td>Measured</td>
<td>1069 V/V</td>
</tr>
</tbody>
</table>

- Much higher expected gain than measured.
- Loading between stages not considered?
DC Coupled, Open Loop at Full Input

- Too much gain, clipping of output wave.
- Need feedback to lower gain and increase feedback.
- Resistor used to sample output voltage and feed back to differential amplifier.
Feedback Approximation

Input Resistance:

\[ R_{IN} = R_B \parallel 2r_\pi \]

Based on necessary gain:

\[ A_{CL} = \frac{V_{OUT,desired}}{V_{IN}} \]

Feedback resistor required:

\[ R_F = A_{CL} R_{IN} \]

\[ R_F \approx 2 \, \text{M}\Omega \]
DC Coupled, Closed Loop Results

- This gain allows for full signal amplification with little distortion and at necessary load power.

<table>
<thead>
<tr>
<th>Gain</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Calculated</td>
<td>535 V/V</td>
</tr>
<tr>
<td>Measured</td>
<td>525 V/V</td>
</tr>
</tbody>
</table>
Frequency Response - Estimation

Low Frequency 3-dB Point  High Frequency 3-dB Point

\[ f_{\text{low}} = \frac{1}{2\pi RC} \]

\[ = \frac{1}{2\pi (3696 \Omega)(1\mu F)} \approx 43 \text{ Hz} \]

Open Loop

- This frequency much harder to theoretically predict.
- Dependent on gain and transistor internal capacitance.
- Use SPICE
Open and Closed Loop Frequency Response

Frequency (Hz)

Gain (dB)
Objectives

<table>
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<tr>
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<th>Achieved</th>
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<td>±24 V</td>
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</tr>
<tr>
<td>Output Signal Power</td>
<td>10 W</td>
<td>10.57 W</td>
</tr>
<tr>
<td>Bandwidth</td>
<td>&gt;10 KHz</td>
<td>35.96 KHz</td>
</tr>
<tr>
<td>Input Impedance</td>
<td>&gt;1 KΩ</td>
<td>3696 KΩ</td>
</tr>
<tr>
<td>Load Impedance</td>
<td>16 Ω</td>
<td>16.3 Ω</td>
</tr>
<tr>
<td>Input Signal Level</td>
<td>50 mV</td>
<td>50 mV</td>
</tr>
</tbody>
</table>
Similar Application – Operational Amplifiers

1. Differential Amplifier
2. Gain Stage
3. Power Amplifier

Would add feedback like in LSA design for stability!
Additional Sources

• http://www.ibiblio.org/kuphaldt/socratic/output/bjtamp_b.pdf
• http://en.wikipedia.org/wiki/Electronic_amplifier
• http://www.eie.polyu.edu.hk/~ensurya/lect_notes/commun_cir/Ch2/Chapter2.htm
• http://ecelab.com/long-tailed-pair.htm
• http://en.wikipedia.org/wiki/Common_emitter
• http://whites.sdsmt.edu/classes/ee320/notes/320Lecture14.pdf
• Microelectronic Circuit, Sedra/Smith, 5th Edition
PNP BJT

(1) Holes injected diffuse across EB
(2) Holes reach BC and drift to C
(3) Holes injected recombine with B electrons
(4) Electrons injected recombine with B holes
(5) Electrons injected diffuse across EB
(6) Reverse bias e or h drift across BC (small)

Remember: p+n for EB so (1) >> (5)
$W_B << L_B$ so (2) >> (3), but (3)#(6)