Chapter 13 Output Stages and Power Amplifiers

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Why Power Amplifiers?



- Cellular phones need 1W of power at the antenna.
- Audio systems deliver tens to hundreds of watts of power.
- Ordinary Voltage/Current amplifiers are not suitable for such applications

Chapter Outline



Power Amplifier Characteristics

- Experiences low load resistance.
- Delivers large current levels.
- Requires large voltage swings.
- Draws a large amount of power from supply.
 - Dissipates a large amount of power, therefore gets "hot".

Power Amplifier Performance Metrics



Power Efficiency

Voltage Rating – Transistor Breakdown voltage

Emitter Follower Large-Signal Behavior I



 \succ As V_{in} increases V_{out} also follows and Q₁ provides more current.

For V_{in}=4.8V, V_{out}=4.0V, I_L=500mA, I_{E1}=532.5mA

Emitter Follower Large-Signal Behavior II





=-0.26V

(c)

However, as V_{in} decreases, V_{out} also decreases, shutting off Q₁ and resulting in a constant V_{out}.

Example 13.1: Emitter Follower

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i.....

$$\succ$$
 V_{in}=0.5V, V_{out}=?



$$V_{in} - V_{BE1} = V_{out} , \frac{V_{out}}{R_L} + I_1 = I_{C1}$$
$$V_{BE1} = V_T \ln(I_{C1} / I_S)$$
$$V_{in} - V_T \ln\left[\left(\frac{V_{out}}{R_L} + I_1\right)\frac{1}{I_S}\right] = V_{out}$$

For
$$V_{in} = 0.5 V$$

 $\Rightarrow V_{out} \approx -211 \text{ mV}$ by a few iterations

Example 13.1: Emitter Follower





Linearity of an Emitter Follower



As V_{in} decreases the output waveform will be clipped, introducing nonlinearity in I/O characteristics.

Push-Pull Stage



As V_{in} increases, Q₁ is on and pushes current into R_L.
 As V_{in} decreases, Q₂ is on and pulls current out of R_L.

Example 13.2: I/O Characteristics for Large Vin



For positive V_{in}, Q₁ shifts the output down and for negative V_{in}, Q₂ shifts the output up.

Overall I/O Characteristics of Push-Pull Stage



> However, for small V_{in} , there is a "dead zone" (both Q_1 and Q_2 are off) in the I/O characteristic, resulting in gross nonlinearity.

Example 13.3: Small-Signal Gain of Push-Pull Stage



The push-pull stage exhibits a gain that tends to unity when either Q₁ or Q₂ is on.

When V_{in} is very small, the gain drops to zero.

Example 13.4: Sinusoidal Response of Push-Pull Stage



For large V_{in}, the output follows the input with a fixed DC offset, however as V_{in} becomes small the output drops to zero and causes "Crossover Distortion."

Improved Push-Pull Stage



> With a battery of V_B inserted between the bases of Q_1 and Q_2 , the dead zone is eliminated.

Implementation of V_B



Since V_B=V_{BE1}+|V_{BE2}|, a natural choice would be two diodes in series.

 \succ I₁ in figure (b) is used to bias the diodes and Q₁.

Example 13.6: Current Flow I



Example 13.8: Current Flow II



Addition of CE Stage



A CE stage (predriver) is added to provide voltage gain from the input to the bases of Q₁ and Q₂.

Bias Point Analysis



For bias point analysis for V_{out}=0, the circuit can be simplified to the one on the right, which resembles a current mirror.

$$I_{C1} = \frac{I_{S,Q1}}{I_{S,D1}} \cdot |I_{C3}|$$

Small-Signal Analysis



> Assuming $2r_D$ is small and $(g_{m1}+g_{m2})R_L$ is much greater than 1,

$$A_{v} = -g_{m4} (r_{\pi 1} \Box r_{\pi 2}) (g_{m1} + g_{m2}) R_{L}$$

Example 13.9: Output Resistance Analysis



$$\left(R_{out} \approx \frac{1}{g_{m1} + g_{m2}} + \frac{r_{O3} \| r_{O4}}{(g_{m1} + g_{m2})(r_{\pi 1} \| r_{\pi 2})}\right)$$

> If β is low, the second term of the output resistance will rise, which will be problematic when driving a small resistance.

Example13.10: Biasing

Compute the required bias current.



Predriver (CE stage): $A_V = 5$ Output Stage: $A_V = 0.8$ for $R_L = 8 \Omega$ $\beta_{npn} = 2\beta_{pnp} = 100, I_{C1} \approx I_{C2}$

$$g_{m1} + g_{m2} = (2 \ \Omega)^{-1} \Longrightarrow g_{m1} \approx g_{m2} \approx (4 \ \Omega)^{-1}$$

Thus, $I_{C1} \approx I_{C2} \approx 6.5 \text{ mA}$
 $r_{\pi 1} \parallel r_{\pi 2} = 400 \ \Omega \parallel 200 \ \Omega = 133 \ \Omega$
 $g_{m4} \cdot (r_{\pi 1} \parallel r_{\pi 2}) \cdot [1 + (g_{m1} + g_{m2}) \cdot R_L] = 4$
 $\Longrightarrow g_{m4} = (133 \ \Omega)^{-1} \Longrightarrow I_{C3} \approx I_{C4} \approx 195 \ \mu\text{A}$

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Problem of Base Current



> 195 μ A of base current in Q₁ can only support 19.5 mA of collector current, insufficient for high current operation (500 mA for 4 V on 8 Ω).

Modification of the PNP Emitter Follower



Instead of having a single PNP as the emitter-follower, it is now combined with an NPN (Q₂), providing a lower output resistance.

Example 13.11: Input Resistance







Comparing with the standard EF,

$$r_{out} = \frac{1}{(\beta_2 + 1)g_{m3}} \approx \frac{1}{(\beta_2 + 1)g_{m3}} \approx \frac{1}{(\beta_2 + 1)g_{m3}}$$

Example 13.11: Input Resistance



Additional Bias Current



> I_1 is added to the base of Q_2 to provide an additional bias current to Q_3 so the capacitance at the base of Q_2 can be charged/discharged quickly. Additional pole at the base of Q_2 .

Example 13.12: Minimum V_{in}



HiFi Design



> As V_{out} becomes more positive, g_m rises and A_v comes closer to unity, resulting in nonlinearity.

Using negative feedback, linearity is improved, providing higher fidelity.

Short-Circuit Protection



Q_s and r are used to "steal" some base current away from Q₁ when the output is accidentally shorted to ground, preventing short-circuit damage.

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Emitter Follower Power Rating



Maximum power dissipated across Q₁ occurs in the absence of a signal.

Example 13.13: Power Dissipation

Avg Power Dissipated in the Current Source I₁



Push-Pull Stage Power Rating



$$P_{av,NPN} = \frac{1}{T} \int_0^{T/2} I_C \cdot V_{CE} dt$$

$$= \frac{1}{T} \int_0^{T/2} \left(V_{CC} - V_P \sin \omega t \right) \cdot \frac{V_P \sin \omega t}{R_L} dt$$

$$= \frac{V_{CC} \cdot V_P}{\pi R_L} - \frac{V_P^2}{4R_L} = \frac{V_P}{R_L} \left(\frac{V_{CC}}{\pi} - \frac{V_P}{4} \right)$$

> No power for half of the period.

Push-Pull Stage Power Rating



No power for half of the period.

• Maximum power occurs between $V_p=0$ and $4V_{cc}/\pi$.

$$P_{av,\max} = \frac{V_{CC}^2 \cdot V_P}{\pi^2 R_L}$$
 when $V_P = 2 \cdot \frac{V_{CC}}{\pi}$

Push-Pull Stage Power Rating

$$P_{av,PNP} = \frac{1}{T} \int_{T/2}^{T} |I_C| \cdot |V_{CE}| dt$$

$$= \frac{1}{T} \int_{T/2}^{T} (V_P \sin \omega t - V_{EE}) \cdot \left(-\frac{V_P \sin \omega t}{R_L} \right) dt$$

$$= \frac{-V_{EE} \cdot V_P}{\pi R_L} - \frac{V_P^2}{4R_L} = \frac{V_P}{R_L} \left(\frac{-V_{EE}}{\pi} - \frac{V_P}{4} \right)$$
(b)
$$Maximum power occurs between V_p=0 and 4V_{CC}/\pi.$$

$$P_{av,max} = \frac{V_{CC}^2 \cdot V_P}{\pi^2 R_L} \text{ when } V_P = 2 \cdot \frac{V_{CC}}{\pi}$$

 π

Heat Sink



Heat sink, provides large surface area to dissipate heat from the chip.

Thermal Runaway Mitigation



$$V_{D1} + V_{D2} = V_T \ln \frac{I_{D1}}{I_{S,D1}} + V_T \ln \frac{I_{D2}}{I_{S,D2}}$$
$$= V_T \ln \frac{I_{D1}I_{D2}}{I_{S,D1}I_{S,D2}}$$
$$V_{BE1} + V_{BE2} = V_T \ln \frac{I_{C1}}{I_{S,Q1}} + V_T \ln \frac{I_{C2}}{I_{S,Q2}}$$
$$= V_T \ln \frac{I_{C1}I_{C2}}{I_{S,Q1}I_{S,Q2}}$$
With the same V_T ,
$$\frac{I_{D1}I_{D2}}{I_{S,D2}} = \frac{I_{C1}I_{C2}}{I_{S,Q1}I_{S,Q2}}$$

Using diode biasing prevents thermal runaway since the currents in Q₁ and Q₂ will track those of D₁ and D₂ as long as their I_s's track with temperature.

Efficiency

Efficiency is defined as the average power delivered to the load divided by the power drawn from the supply

 $\eta = \frac{\text{Power Delivered to Load}}{\text{Power Drawn From Supply Voltage}} = \frac{P_{out}}{P_{out} + P_{ckt}}$

$$\frac{Emitter \ Follower}{V_P^2/2R_L}$$

$$\eta_{EF} = \frac{V_P^2/2R_L}{V_P^2/2R_L + I_1(V_{CC} - V_P/2) - I_1 \cdot V_{EE}}$$

$$= \frac{V_P}{4V_{CC}} \text{ if } I_1 = \frac{V_P}{R_L} \text{ and } -V_{EE} = V_{CC}$$

Maximum efficiency for EF is 25%.

Example 13.15: Efficiency of EF

EF designed for full swing operates with half swing.



Efficiency



Maximum efficiency for PP is 78.5%.

Example 13.16: Efficiency incl. Predriver

$$I_{1} = (V_{P}/R_{L})/\beta$$

$$\eta = \frac{\frac{V_{P}^{2}}{2R_{L}}}{\frac{2V_{P}V_{CC}}{\pi R_{L}} + (V_{CC} - V_{EE})\frac{V_{P}}{\beta R_{L}}}$$

$$= \frac{1}{4} \frac{V_{P}}{V_{CC}/\pi + V_{CC}/\beta}$$

$$= \frac{1}{4} \frac{1}{\frac{1}{\pi} + \frac{1}{\beta}} \frac{V_{P}}{V_{CC}}$$

Power Amplifier Classes

