F12 – Output Stages

Outline
• Classification of output stages
  • Class A
  • Class B
  • Class AB
  • Class C
  • Class D
• Operation and power efficiency of class A, B, and AB
• CMOS implementation of class AB output stage
• Power transistors

Reading Guide  Sedra/Smith 7ed int
• Chapter 11.1-5 (output stages)
• (Chapter 11.6 (variations))
• Chapter 11.7 (CMOS AB stage)
• (Chapter 11.8-10 (PAs, power devices))

Problems  Sedra/Smith 7ed int
• P11.2, 11.11, 11.19(a-b), 11.56
Classification of Output Stages

- Output stages are primarily classified by their periodic active angle, $\theta$

- Linear and “quasi-linear complementary” amplifiers
  - Class A: $\theta = 360^\circ$
  - Class B: $\theta = 180^\circ$
  - Class AB: $180^\circ < \theta \ll 360^\circ$

- Small angle (tuned resonator) amplifiers
  - Class C: $0^\circ < \theta < 180^\circ$

- Pulse width modulated (switching) amplifiers
  - Class D: $\theta = 360^\circ$ non-linear

- ... and more sophisticated classes (E, F, G, H, etc.)
Source(/ Emitter) Follower as an Output Stage

- Common drain(/ collector) a.k.a. source(/ emitter) follower
  - High input resistance
    \[ R_i = \infty \]
  - Voltage buffer
    \[ A_{vo} \approx \frac{1}{1 + \chi} \]
  - Low output resistance
    \[ R_o \approx \frac{1}{g_m(1 + \chi)} \]

Ideal input/ output resistance for a voltage amplifier, but gain must be provided by previous stages.
Class A

- Common drain/ emitter, Q1, with active load, Q2

- Balanced supplies ($\pm V_{CC}$) allow load to ground
  \[ V_{EE} = -V_{CC} \]

- Bias/ load should be designed to support rail-to-rail signal operation
  - Positive output: Q1 on
  - Negative output: Q1 off
  \[ v_o = -IR_L \leq -V_{CC} \]
  \[ \iff \quad R_L \geq \frac{V_{CC}}{I} \]
Class A: Large Signal Operation

- Non-inverting operation centred on $i_{E1} = I$ and $v_O = 0$
  - Rail-to-rail operation (neglecting Q1 and Q2 $v_{CESat}$)
    \[ R_L \geq \frac{V_{CC}}{I} \Rightarrow -V_{CC} < v_O < V_{CC} \]
- High output (Q1 on)
  \[ v_O = V_{CC}, \quad i_{E1} = 2I \]
  \[ i_L = i_{E1} - I = I \]
- Low output (Q1 off)
  \[ v_O = -V_{CC}, \quad i_{E1} = 0 \]
  \[ i_L = i_{E1} - I = -I \]
Class A: Signal Waveforms

- Rail-to-rail output voltage swing (neglecting $v_{CESat}$)
  - Load resistance selected to support rail-to-rail operation
    \[ R_L = \frac{V_{CC}}{I} \]
  - Collector-emitter voltage shifted and inverted w.r.t output
    \[ -V_{CC} < v_{CE1} = V_{CC} - v_O < V_{CC} \]
- Current swing
  \[ 0 < i_{C1} \approx I + v_O R_L < 2I \]
- Power dissipated in $Q1$
  \[ 0 < p_{D1} = v_{CE1} i_{C1} < V_{CC} I \]
Class A: Power Efficiency

- Power efficiency
  - Ratio of load power, $P_L$, to supply power, $P_S$
    \[
    \eta = \frac{P_L}{P_S} = \frac{1}{4} \left( \frac{\hat{V}_o}{IR_L} \right) \left( \frac{\hat{V}_o}{V_{CC}} \right) \leq 25\% \\
    10\% < \eta_{typical} < 20\%
    \]
  - Harmonic output assumed
    \[
    v_O = \hat{V}_o \sin(\omega t) = \hat{V}_o \sin \left( \frac{2\pi}{T} t \right)
    \]
  - Load power
    \[
    P_L = \frac{v_O^2}{R_L} = \frac{1}{2} \frac{\hat{V}_o^2}{R_L}
    \]
  - Supply power
    \[
    P_S = P_{S+} + P_{S-} = 2V_{CC}I
    \]

Power dissipation monotonically reduced with output voltage level, but high quiescent value and low maximum efficiency.
Complementary Emitter(Source) Follower as an Output Stage

- Complementary push-pull configuration
  - One transistor active
  - One transistor cutoff

Q1 sources (pushes) load current, Q2 sinks (pulls) load current.
Class B

- Complementary push-pull configuration
- Balanced supplies ($\pm V_{CC}$) allow load to ground
- Supports rail-to-rail operation (within $v_{CEsat}$)
  - Positive output: QN on, QP off
  - Negative output: QP on, QN off
- Dead band about zero input
  - Both QN and QP cutoff
Class B: Crossover Distortion

- Dead band due to conduction threshold voltage
  \[ |v_I| < v_{BEactive} \Rightarrow v_O \approx 0 \]
- Signal distortion at zero-crossing

Crossover distortion can be circumvented through use of clever biasing.
Class B: Power Efficiency

- Power efficiency
  - Ratio of load power, $P_L$, to supply power, $P_S$
    \[ \eta = \frac{P_L}{P_S} = \frac{\pi}{4} \left( \frac{\hat{V}_o}{V_{CC}} \right) \leq 78.5\% \]
    \[ 40\% < \eta_{\text{typical}} < 60\% \]

- Harmonic output assumed
  \[ v_o = \hat{V}_o \sin(\omega t) = \hat{V}_o \sin \left( \frac{2\pi}{T} t \right) \]

- Load power
  \[ P_L = \frac{v_o^2}{R_L} = \frac{1}{2} \frac{\hat{V}_o^2}{R_L} \]

- Supply power
  \[ P_S = P_{S+} + P_{S-} = \frac{2}{\pi} \frac{\hat{V}_o}{R_L} V_{CC} \]

\[ P_D = P_{\text{dissipated}} = P_L - P_S = \frac{\hat{V}_o}{R_L} \left( \frac{2}{\pi} V_{CC} - \frac{1}{2} \hat{V}_o \right) \]

Power dissipation low for low and high output voltage, and quite good maximum efficiency.
Class B: Single Supply

- Shifted positive supply
  \[ V'_CC = V_{CC} + V_{EE} = \{V_{EE} = V_{CC}\} = 2V_{CC} \]

- Grounded current sink
  \[ V'_{EE} = -V_{EE} + V_{EE} = 0 \]

- Capacitively coupled load to ground
  - Separates dc from signal
Attractive to eliminate class B conduction threshold; why and how?
Class AB

- Class A at very low bias, or bias on a class B stage
  - Removes conduction threshold, no crossover distortion
  - Small quiescent power dissipation

Elimination of harmonic distortion due to dead band, at the cost of efficiency and complexity.
Class AB: Quiescent Current and Large Signal Operation

- Input bias generates quiescent current
  \[ i_N \bigg|_{v_O=0} = i_P \bigg|_{v_O=0} = I_Q = I_S \exp \left( \frac{V_{BB}}{2V_T} \right) \]

- Positive output voltage (negative just opposite)
  - Output follows input
    \[ v_O = v_i + \frac{V_{BB}}{2} - v_{BEN}, \quad i_L = \frac{v_O}{R_L} \]
  - Incremental load current supplied by QN, which requires increased QN base drive
    \[ i_N = i_P + i_L, \quad v_{BEN} + v_{EBP} = V_{BB} \]
  - Product of device currents remain constant
    \[ i_Ni_P = I_Q^2 \Rightarrow i_N^2 - i_Li_N - I_Q^2 = 0 \]

Similar to class B, but reduced distortion.
Biasing the BJT Class AB Input

- Diodes
  - Simple but primitive

- Base-emitter multiplier
  - Design ratio using resistances

\[
I_R = \frac{V_{BE1}}{R_1}
\]

\[
V_{BB} = I_R(R_1 + R_2) = V_{BE1} \left(1 + \frac{R_2}{R_1}\right)
\]
(Class AB: BJT Variations)

- Input emitter followers
  - Buffers input signal
  - Provides AB biasing

- Compound devices boost performance
  - Darlington configuration
  - Compound PNP
(Protection Circuits)

- Output short circuit protection, protects against too high load current
  - Q5 normally off
  - High current in $R_{E1}$ turns Q5 on
  - Q5 on turns Q1 off

- Thermal shutdown, protects chip against meltdown
  - Q2 normally off
  - Z1 positive temperature coefficient
  - Q1 negative temperature coefficient
  - High temp turns Q2 on
  - Q2 on robs bias from another stage

Protect the amplifier from the user.
Class AB: Classical CMOS Configuration

- Complementary source follower with diode connected input devices
  - Equivalent to BJT AB with diode bias
  - Voltage buffer
  - Low output resistance
  - Limits to the output swing
    - QN and QP overdrive voltages
    - Input circuit active load overdrive voltage
    - Bias current source overdrive voltage

\[-V_{SS} + V_{OVI} + |V_{tp}| + |v_{OVP}| < v_o < (V_{DD} - V_{OVB} - V_{tn} - v_{OVN})\]

- Quiescent current due to input bias

\[i_{DN}|_{v_o=0} = i_{DP}|_{v_o=0} = I_Q = I_{BIAS} \frac{(W/L)_n}{(W/L)_1}\]
Class AB: Wide Swing CMOS Configuration

• Complementary push-pull common source
  • Provides high voltage gain, as compared to follower
  • Moderately high output impedance

\[ R_o = r_{on} \parallel r_{op} \]

• Output swing improved to within an overdrive voltage from the supplies

\[-V_{SS} + v_{OVN} < v_o < V_{DD} - v_{OVN} \]

Output resistance can be improved by feedback.
Class D: High Efficiency Switching Amplifier

- High efficiency (ideally 100%)
  - Rapid switch between on and off yields only device power dissipation in a brief moment
  - On or off, no simultaneous voltage and current
    \[ P_L = v_L i_L \approx V_S I_S = P_S \]

- Transmitter
  - Pulse width modulation (PWM) of signal at a high frequency w.r.t. signal frequency

- Receiver
  - Demodulation by low-pass filtering (moving average)

Power dissipation is high when there is current and voltage simultaneously.
Is it possible to build power amplifiers (PAs) from “normal” transistors?
(Power Transistors)

- High current requires large device: low frequency bandwidth
- High thermal dissipation: temperature coefficients and heat sinks
- High electric fields: velocity saturation