Class B Output Stage

- Class B Operation
- Multisim Simulations
- Class B Power Efficiency
Class B Amplifier Operation

Class B – Amplifier BJT conducts for positive-half of \( v_I \) cycle.

Amp conducts for all \( v_I \) s.t.:

\[
v_I \geq 0 \, V \Rightarrow V_B = 0.7 \, V
\]

or

\[
v_I \geq 0.7 \, V \Rightarrow V_B = 0 \, V
\]

Usually assume Class B operation if \( V_B = 0 \, V \).

Transistor cut off \((i_C = 0)\) if:

\[
v_I + V_B < 0.7 \, V
\]

NOTE: 1. when \( v_I = 0, \, i_C = 0 \)

2. a 2\textsuperscript{nd} class B BJT is needed to conduct for the negative \( v_I \) cycle.
The Class B Output Stage

I. For $v_i > 0.7 \text{ V}$
   \[ v_{\text{BEN}} = v_i - v_O \]
   \[ v_O = v_i - 0.7 \text{ V} \]

   For $v_i < -0.7 \text{ V}$
   \[ v_{\text{EBP}} = v_O - v_i \]
   \[ v_O = v_i + 0.7 \text{ V} \]

II. For $v_i < V_{\text{BEP}} = -0.7 \text{ V}$, $Q_p = ON$, $Q_N = OFF$.
   a. $i_L = i_{\text{EN}} \approx i_{\text{CN}}$
   b. $Q_N$ saturates if $v_O > V_{\text{CC}} - V_{\text{CE-sat}}$
   c. $Q_P$ is cut off for $v_i > -0.7 \text{ V}$.

   The output voltage $v_O$ follows the input $v_i$, less the $Q_N$ $V_{BE}$ drop, up to $Q_N$ saturation.

0. For $v_i = 0 \text{ V}$, $Q_N$ and $Q_P$ cutoff.
   \[ v_O = 0 \text{ V} \]
Class B Amplifier VTC Plot

\[ v_o = v_i - 0.7 \, V \]
For:
\[ 0.7 \, V < v_i < (V_{CC} - V_{CENsat}) + 0.7 \, V \]

\[ v_o = 0 \, V \]
For:
\[ -0.7 \, V < v_i < 0.7 \, V \]

\[ v_o = v_i + 0.7 \, V \]
For:
\[ -(V_{CC} - V_{ECPsat}) - 0.7 \, V < v_i < -0.7 \, V \]
Crossover distortion in audio power amps produces unpleasant sounds.
Multisim Simulation Class B VTC
Multisim Simulation Class B VTC - cont.
Multisim Simulation Class B VTC - cont.
The “dead band” from $V_{BEP} = 0.7 \, V < v_i < V_{BEN} = 0.7 \, V$ causes crossover distortion. This distortion is severe, particularly for low voltage signals.
Class B Power Analysis

Simplifying Assumptions:
1. Ignore the dead-zone in $v_o$.
2. Let $v_{CEN-sat} = v_{ECP-sat} = 0 \, V \Rightarrow$ maximum $v_o$ swing is $-V_{CC} \leq v_o \leq V_{CC}$

The average power to the load resistor:

$$P_{L-av} = V_{o-rms} I_{o-rms} = \frac{V_{o-rms}^2}{R_L} = \frac{1}{2} \frac{V_{o-peak}^2}{R_L}$$

The average power delivered by the positive $+V_{CC}$ power supply over the positive half-cycle (current is zero from $T/2$ to $T$):

$$P_{DP-av} = \frac{1}{T} \int_0^{T/2} V_{CC} i_{CN} \, dt = \frac{1}{T} \int_0^{T/2} V_{CC} i_L \, dt = \frac{1}{T} \int_0^{T/2} V_{CC} \frac{V_{o-peak}}{R_L} \sin \left( \frac{2\pi}{T} t \right) \, dt$$
Class B Power Analysis - cont.

\[ P_{DP-av} = \frac{1}{T} V_C \frac{V_{o-peak}}{R_L} \frac{T^2}{2} \int_0^T \sin \left( \frac{2\pi}{T} t \right) dt \]

Recalling from calculus \( \int \sin(ax) \, dx = -\frac{1}{a} \cos(ax) \)

\[ P_{DP-av} = \frac{1}{T} V_C \frac{V_{o-peak}}{R_L} \left( -\frac{T}{2\pi} \cos \left( \frac{2\pi}{T} t \right) \right) \bigg|_{t=0}^{t=T/2} \]

\[ P_{DP-av} = -\frac{1}{2\pi} \frac{V_{o-peak}}{R_L} V_C \left\{ \cos \left( \frac{2}{T} \pi \frac{T}{2} \right) - \cos \left( \frac{2}{T} \pi 0 \right) \right\} \]

\[ P_{DP-av} = -\frac{1}{2\pi} \frac{V_{o-peak}}{R_L} V_C \left\{ -1 \right\} \]
Class B Power Analysis - cont.

Power delivered by the negative $-V_{CC}$ power source is equal to that for $+V_{CC}$:

$$P_{DN-av} = P_{DP-av} = \frac{1}{\pi} \frac{V_{o-peak}}{R_L} V_{CC}$$

Hence:

$$P_{D-av} = P_{DP-av} + P_{DN-av} = \frac{2}{\pi} \frac{V_{o-peak}}{R_L} V_{CC}$$

The power conversion efficiency of the class B amplifier (accurate for $|V_{o-peak}| > 0.7$ V) is:

$$\eta = \frac{P_{L-av}}{P_{D-av}} = \frac{\frac{1}{2} \frac{V^2_{o-peak}}{R_L}}{\frac{2}{\pi} \frac{V_{o-peak}}{R_L} V_{CC}} = \frac{\pi}{4} \frac{V_{o-peak}}{V_{CC}}$$
Class B Power Analysis - cont.

Maximum Class B power conversion efficiency:

Since we assume \(-V_{CC} \leq v_o \leq V_{CC}\)

\[
\eta = \frac{\pi}{4} \frac{V_{o-peak}}{V_{CC}} \Rightarrow \eta_{max} = \frac{\pi}{4} = 0.785 \text{ or } 78.5\%
\]

Recall for Class A: \(\eta_{max} = 0.25 \text{ or } 25\%\)

Power Dissipation:

Class B power dissipated in the transistors:

\[
P_{Disp} = P_{D-av} - P_L = \frac{2}{\pi} \frac{V_{o-peak}}{R_L} V_{CC} - \frac{1}{2} \frac{V_{o-peak}^2}{R_L}
\]
Class B Power Analysis - cont.

Note that the power dissipation goes to zero as \( V_{o\text{-peak}} \) approaches zero (More precisely, it's zero if \( V_{o\text{-peak}} \) is less than 0.7 V):

\[
P_{\text{Disp}} = P_{D-av} - P_{L-av} = \frac{2}{\pi} \frac{V_{o\text{-peak}}}{R_L} V_{CC} - \frac{1}{2} \frac{V_{o\text{-peak}}^2}{R_L}
\]

To estimate maximum \( P_{\text{Disp}} \): set derivative of \( P_{\text{Disp}} \) w.r.t. \( V_{o\text{-peak}} \) to zero, i.e.

\[
\frac{d P_{\text{Disp}}}{d V_{o\text{-peak}}} = \frac{2}{\pi} \frac{V_{CC}}{R_L} - \frac{V_{o\text{-peak}}}{R_L} = 0 \quad \Rightarrow \quad V_{o\text{-peak}} = \frac{2}{\pi} V_{CC} < V_{CC}
\]

\[
P_{\text{Disp(max)}} = \frac{4}{\pi^2} \frac{V_{CC}^2}{R_L} - \frac{1}{2} \frac{4}{\pi^2} \frac{V_{CC}^2}{R_L} = \frac{2}{\pi^2} \frac{V_{CC}^2}{R_L}
\]

\( \frac{1}{2} P_{\text{Disp(max)}} \) is dissipated in \( Q_N \) and \( \frac{1}{2} P_{\text{Disp(max)}} \) is dissipated in \( Q_P \).
**Class B Power Analysis Summary**

Power from sources:

\[ P_{D-av} = \frac{2}{\pi} \frac{V_{o-peak}}{R_L} V_{CC} \]

\[ P_{D-av(max)} = \frac{2}{\pi} \frac{V_{CC}^2}{R_L} \]

Power output to load:

\[ P_{L-av} = \frac{1}{2} \frac{V_{o-peak}^2}{R_L} \]

\[ P_{L-av(max)} = \frac{1}{2} \frac{V_{CC}^2}{R_L} \]

Power Conversion Efficiency:

\[ \eta = \frac{\pi}{4} \frac{V_{o-peak}}{V_{CC}} \]

\[ \eta_{max} = \frac{\pi}{4} \approx 0.785 \]

Transistor dissipation \( Q_N + Q_P \):

\[ P_{Disp} = \frac{2}{\pi} \frac{V_{o-peak}}{R_L} V_{CC} - \frac{1}{2} \frac{V_{o-peak}^2}{R_L} \]

\[ P_{Disp(max)} = \frac{2}{\pi^2} \frac{V_{CC}^2}{R_L} \]

Max dissipation at:

\[ V_{o-peak} = \frac{2}{\pi} V_{CC} \]

\[ \eta_{max-Disp} = 0.5 \]
Power Dissipation Function Plot

Let $V_{CC} = 12 \, \text{V}$ and $R_L = 100 \, \Omega$

$$P_{Disp(max)} = \frac{2V_{CC}^2}{\pi^2 R_L} = 0.29 \, \text{W}$$

$$P_{Disp} = \frac{2}{\pi} \frac{V_{o-peak}^2}{R_L} V_{CC} - \frac{1}{2} \frac{V_{o-peak}^2}{R_L}$$

Not accurate for small $V_{o-peak}$. 

2008 Kenneth R. Laker (based on P. V. Lopresti 2006) updated 05Nov08 KRL
Power Conversion Efficiency vs. Output Voltage Amplitude

Let $V_{CC} = 12 \text{ V}$ and $v_o = v_i - 0.7 \text{ V}$

Efficiency ($\eta$)

$\eta = \frac{\pi}{4} \frac{V_{o-peak}}{V_{CC}}$

$\eta_{max} = 0.785$
Class B Audio Amplifier Example

It is required to design a Class B output stage to deliver an average power of 20 W to an 8 Ω speaker load.

To avoid saturation of the transistors and nonlinear distortion, the power supply $V_{CC}$ is to be 5 V greater than peak output voltage.

1. Determine the $V_{CC}$ required.
2. Determine peak current drawn from each power supply.
3. Determine the total power drawn from the power supplies.
4. Determine the power conversion efficiency.
5. Determine the max power each transistor must be able to dissipate safely.
Class B Audio Amplifier Example - cont.

SOLUTION:
1. Determine the $V_{CC}$ required.

\[ P_{L-av} = 20 \, W \quad \text{and} \quad R_L = 8 \, \Omega \]

\[ P_{L-av} = \frac{1}{2} \frac{V_{o-peak}^2}{R_L} = 20 \, W \quad \Rightarrow \quad V_{o-peak} = \sqrt{2 \cdot P_{L-av} \cdot R_L} = \sqrt{2 \times 20 \times 8} = 17.9 \, V \]

\[ V_{CC} = V_{o-peak} + 5 \, V = 17.9 \, V + 5 \, V = 23 \, V \]

2. Determine peak current drawn from each power supply.

\[ I_{o-peak} = \frac{V_{o-peak}}{R_L} = \frac{17.9 \, V}{8 \, \Omega} = 2.24 \, A \]
Class B Audio Amplifier Example - cont.

SOLUTION cont.:

3. Determine the total power drawn from the power supplies.

\[
P_{D-av} = 2 \frac{V_{o-peak}}{\pi} \frac{V_{cc}}{R_L} = 2 \frac{17.9 \, V}{8 \, \Omega} \cdot 23 \, V = 32.8 \, W
\]

4. Determine the power conversion efficiency.

\[
\eta = \frac{\pi}{4} \frac{V_{o-peak}}{V_{cc}} = \frac{\pi}{4} \frac{17.9 \, V}{23 \, V} = 0.61 \text{ or } 61 \%
\]

5. Determine the max power each transistor must dissipate safely.

\[
P_{DispN(max)} = P_{DispP(max)} = \frac{1}{2} P_{Disp(max)} = \frac{1}{\pi^2} \frac{V_{cc}^2}{R_L} = \frac{1}{\pi^2} \frac{(23 \, V)^2}{8 \, \Omega} = 6.7 \, W
\]
**Multisim Simulation – Max Power Dissipation**

\[ v_O = v_I - 0.7V \]

\[ P_{DP-av} = \frac{1}{\pi} \frac{V_{o-peak}}{R_L} V_{CC} \]

\[ = 0.265 \text{ W} \]

\[ V_{I-peak} = 7.63 \text{ V} \]

\[ P_{DN-av} = \frac{1}{\pi} \frac{V_{o-peak}}{R_L} V_{CC} \]

\[ = 0.265 \text{ W} \]

\[ P_{L-av} = \frac{1}{2} \frac{V^2_{o-peak}}{R_L} \]

\[ = 0.240 \text{ W} \]

\[ v_O = v_I + 0.7V \]

\[ \eta_{theory} = \frac{P_{L-av}}{P_{DP-av} + P_{DN-av}} = \frac{0.240}{0.265 + 0.265} = 0.45 \]

\[ \eta_{sim} = \frac{P_{L-av}}{P_{DP-av} + P_{DN-av}} = \frac{0.2198}{0.2429 + 0.2449} = 0.45 \]

2008 Kenneth R. Laker (based on P. V. Lopresti 2006) updated 05Nov08 KRL
Multisim Simulation – Max Power Conversion Efficiency

\[ P_{DP - av} - P_{DN - av} + P_{L - av} = \]

\[ \eta_{sim} = \frac{P_{L - av}}{P_{DP - av} + P_{DN - av}} = \frac{0.6772}{0.4231 + 0.4239} = 0.79 \]

\[ V_{i\text{-peak}} = 12.7 \, V \]
Anticipating Class AB – Eliminating Crossover Distortion

If we bias the bases of the emitter follower pair, we can set both transistors on the verge of conduction – or have them conduct a small bias current with zero signal input:

\[ \frac{V_{BB}}{2} \approx 0.7 \ \text{V}. \]

Class AB is a compromise between Class and Class B
Summary

Class B advantages:
1. Much higher power conversion efficiency than class A for large signal amplitudes.
2. Zero power dissipation with zero input.

Class B disadvantage:
Higher distortion than class A, especially at low input amplitudes.

Class AB operation is a compromise mode:
1. Delivering better linearity than class B, with reduced efficiency.
2. Delivering better efficiency than class A, with reduced linearity.