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Single-Stage BJT Amplifier Clipping Levels

The clipping levels of a single-stage amplifier are caused by over driving the transistor so that it either saturates or cuts off. Ideally, an amplifier should be designed so that it exhibits symmetrical clipping. That is, the amplifier should be able to put out positive and negative peak levels that are equal to each. This may not be the case for pulse amplifiers where the input signal is either positive or negative, but not both. The clipping levels of the common-emitter and common-collector amplifiers are derived in the following. The analysis assumes that the ac coupling capacitors in the circuit can be replaced with dc batteries having the same dc voltages as the capacitors.

The Common-Emitter Amplifier

Fig. 1 shows the circuit diagram of a single stage common-emitter amplifier with the input, output, and emitter coupling capacitors replaced with dc batteries. The battery voltages are equal to the voltages across the capacitors C_1, C_2, and C_E that the batteries replace. By superposition, they are given by

$$V_1 = \frac{V^+ R_2 + V^- R_1}{R_1 + R_2} - I_B R_1 \| R_2$$

$$V_2 = V^+ - I_C R_C$$

$$V_3 = V^- + I_E R_E$$

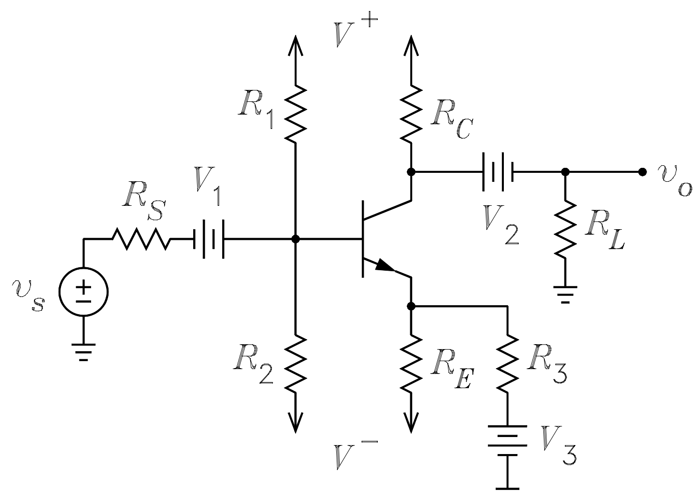

Figure 1: Common-emitter Amplifier.

The positive clipping level is calculated by assuming that the input voltage v_S goes negative until the BJT cuts off, i.e. it becomes an open circuit. The equivalent circuit is shown in Fig. 2. Under these conditions, the positive peak output voltage is given by

$$v_O^+ = \left(V^+ - V_2\right) \frac{R_L}{R_C + R_L} = I_C R_C \frac{R_L}{R_C + R_L} = I_C R_C \| R_L$$

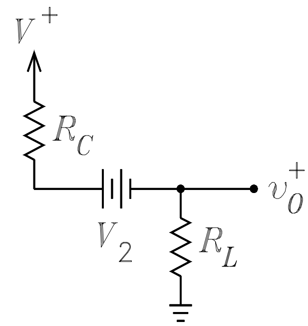

Figure 2: Circuit for calculating v_O^+.

The negative clipping level is calculated by assuming that the input voltage v_S goes positive until the BJT saturates. In this case, the collector-emitter voltage becomes small, ideally zero. We denote the collector-emitter saturation voltage by V_{CEsat}. To calculate the negative peak output voltage, it will be assumed that the base current is small enough to be neglected at the point that the BJT saturates. The equivalent circuit is shown in Fig. 3. Looking to the left of R_L, the Norton equivalent circuit consists of a current i_N and parallel resistance R_N. By superposition, these are given by

$$\begin{aligned} i_N &= \frac{V^+}{R_C} + \frac{V^-}{R_E} + \frac{V_3}{R_3} + \frac{V_{CEsat}}{R_E \| R_3} - \frac{V_2}{R_N} \\ &= \frac{V^+}{R_C} + \frac{V^-}{R_E} + \frac{V^- + I_E R_E}{R_3} + \frac{V_{CEsat}}{R_E \| R_3} - \frac{V^+ - I_C R_C}{R_N} \end{aligned}$$

$$R_N = R_C \| R_E \| R_3$$

The negative clipping level is is given by

$$\begin{aligned} v_O^- &= i_N R_N \| R_L \\ &= \left(\frac{V^+}{R_C} + \frac{V^-}{R_E} + \frac{V^- + I_E R_E}{R_3} + \frac{V_{CEsat}}{R_E \| R_3} - \frac{V^+ - I_C R_C}{R_N} \right) R_C \| R_E \| R_3 \| R_L \\ &= \left(\frac{-V^+ + V^- + V_{CEsat}}{R_E \| R_3} + \frac{I_C R_E}{\alpha R_3} + \frac{I_C R_C}{R_C \| R_E \| R_3} \right) R_C \| R_E \| R_3 \| R_L \end{aligned}$$

where $I_E = I_C / \alpha$ has been used.

The condition for symmetrical clipping is $v_O^+ = -v_O^-$. This condition leads to

$$I_C R_C \| R_L = \left(\frac{V^+ - V^- - V_{CEsat}}{R_E \| R_3} - \frac{I_C R_E}{\alpha R_3} - \frac{I_C R_C}{R_C \| R_E \| R_3} \right) R_C \| R_E \| R_3 \| R_L$$

This can be solved for I_C to obtain

$$\begin{aligned} I_C &= \frac{\dfrac{V^+ - V^- - V_{CEsat}}{R_E \| R_3}}{\dfrac{R_C \| R_L}{R_C \| R_E \| R_3 \| R_L} + \dfrac{R_E}{\alpha R_3} + \dfrac{R_C}{R_C \| R_E \| R_3}} \\ &= \frac{V^+ - V^- - V_{CEsat}}{R_E \| R_3 \left(2 + \dfrac{R_E}{\alpha R_3} \right) + R_C \| R_L \left(2 + \dfrac{R_C}{R_L} \right)} \end{aligned}$$

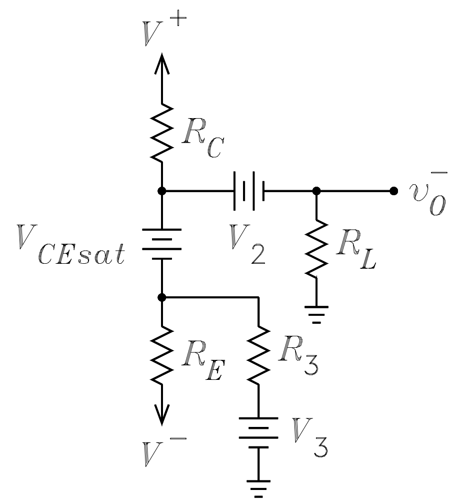

Figure 3: Circuit for calculating v_O^-.

When this condition is satisfied, the common-emitter amplifier will clip symmetrically on the positive and negative peaks.

Example 1 *For the CE amplifier of Fig. 1, it is given that* $R_s = 5\,\mathrm{k\Omega}$, $R_1 = 120\,\mathrm{k\Omega}$, $R_2 = 100\,\mathrm{k\Omega}$, $R_C = 4.3\,\mathrm{k\Omega}$, $R_E = 5.6\,\mathrm{k\Omega}$, $R_3 = 100\,\Omega$, $R_L = 20\,\mathrm{k\Omega}$, $V^+ = 15\,\mathrm{V}$, $V^- = -15\,\mathrm{V}$, $V_{BE} = 0.65\,\mathrm{V}$, $\beta = 99$, $\alpha = 0.99$, $r_x = 20\,\Omega$, $V_A = 100\,\mathrm{V}$, $V_{CEsat} = 0.2\,\mathrm{V}$ *and* $V_T = 0.025\,\mathrm{V}$. *Solve for the positive and negative output clipping voltages. Calculate the value of* I_E *for symmetrical clipping. What are the resultant clipping levels?*

Solution. For the dc bias solution, replace all capacitors with open circuits. The Thévenin voltage and resistance seen looking out of the base are

$$V_{BB} = \frac{V^+R_2 + V^-R_1}{R_1 + R_2} = -1.364\,\mathrm{V} \qquad R_{BB} = R_1 \| R_2 = 54.55\,\mathrm{k\Omega}$$

The Thévenin voltage and resistance seen looking out of the emitter are $V_{EE} = V^-$ and $R_{EE} = R_E$. The bias equation for I_E is

$$I_E = \frac{V_{BB} - V_{EE} - V_{BE}}{R_{BB}/\left(1+\beta\right) + R_{EE}} = 2.113\,\mathrm{mA}$$

The clipping voltages are given by

$$v_O^+ = I_C R_C \| R_L = 7.61\,\mathrm{V}$$

$$\begin{aligned} v_O^- &= \left(\frac{-V^+ + V^- + V_{CEsat}}{R_E\|R_3} + \frac{I_E R_E}{R_3} + \frac{\alpha I_E R_C}{R_C\|R_E\|R_3}\right) R_C\|R_E\|R_3\|R_L \\ &= -4.45\,\mathrm{V} \end{aligned}$$

The value of I_E for symmetrical clipping is

$$I_E = \frac{I_C}{\alpha} = \frac{1}{\alpha}\frac{V^+ - V^- - V_{CEsat}}{R_E\|R_3\left(2 + \dfrac{R_E}{\alpha R_3}\right) + R_C\|R_L\left(2 + \dfrac{R_C}{R_L}\right)} = 2.30\,\mathrm{mA}$$

To achieve this, either R_1, R_2, or both could be adjusted. The change in bias current would also change the small-signal gain. The new clipping levels are

$$v_O^+ = -v_O^- = I_C R_C \| R_L = 6.86\,\mathrm{V}$$

The Common-Collector Amplifier

Fig. 4 shows the circuit diagram of a single stage common-emitter amplifier with the input, output, and emitter coupling capacitors replaced with dc batteries. The battery voltages are equal to the voltages across the capacitors C_1, C_2, and C_E that the batteries replace. By superposition, they are given by

$$V_1 = \frac{V^+ R_2 + V^- R_1}{R_1 + R_2} - I_B R_1 \| R_2$$

$$V_2 = V^- + I_E R_E$$

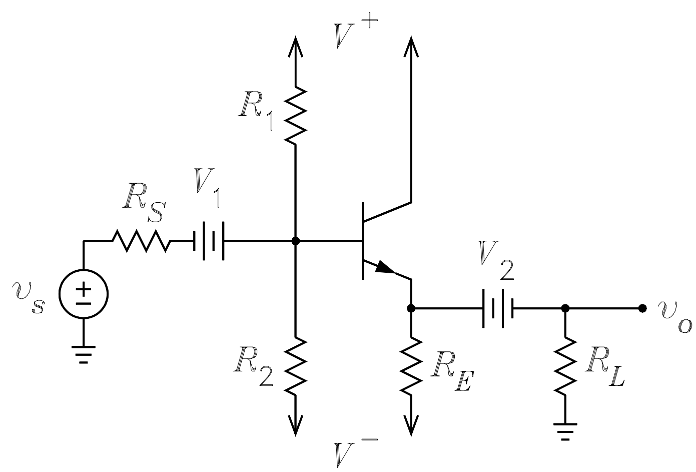

Figure 4: Common-collector amplifier.

The positive clipping level is calculated by assuming that the input voltage v_S goes positive until the BJT saturates. In this case, the collector-emitter voltage becomes small, ideally zero. We denote the collector-emitter saturation voltage by V_{CEsat}. To calculate the positive peak output voltage, it will be assumed that the base current is small enough to be neglected at the point that the BJT saturates. The equivalent circuit is shown in Fig. 5. The output voltage is given by

$$v_O^+ = V^+ - V_{CEsat} - V_2 = V^+ - V_{CEsat} - \left(V^- + I_E R_E\right)$$

The negative clipping level is calculated by assuming that the input voltage v_S goes negative until the BJT cuts off, i.e. it becomes an open circuit. The equivalent circuit is shown in Fig. 6. Under these conditions, the negative peak output voltage is given by

$$v_O^- = \left(V^- - V_2\right) \frac{R_L}{R_E + R_L} = \left[V^- - \left(V^- + I_E R_E\right)\right] \frac{R_L}{R_E + R_L} = -I_E R_E \| R_L$$

The condition for symmetrical clipping is $v_O^+ = -v_O^-$. This condition leads to the condition

$$\left[V^+ - V_{CEsat} - \left(V^- + I_E R_E\right)\right] \frac{R_L}{R_E + R_L} = I_E R_E \| R_L$$

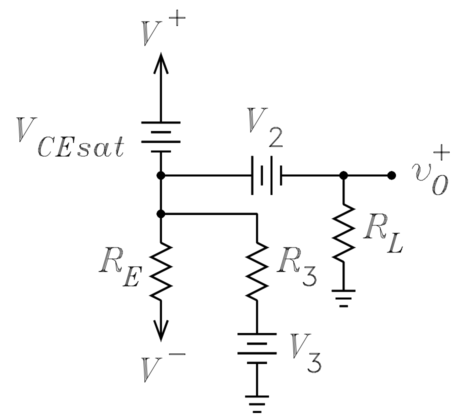

Figure 5: Circuit for calculating v_O^+.

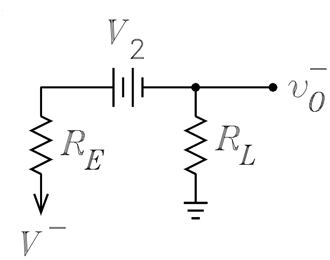

Figure 6: Circuit for calculating v_O^-.

This can be solved for the required dc bias voltage V_X across the emitter resistor R_E to obtain

$$V_X = I_E R_E = \frac{1}{2}\left(V^+ - V_{CEsat} - V^-\right)$$

Note that this is not a function of R_L.

Let the symmetrical clipping voltage be denoted by v_{CL}. From the equation for v_O^-, it is given by

$$v_{CL} = -v_O^- = I_E R_E \| R_L = I_E \frac{R_E R_L}{R_E + R_L} = V_X \frac{R_L}{R_E + R_L}$$

This equation can be solved for R_E to obtain

$$R_E = \left(\frac{V_X}{v_{CL}} - 1\right) R_L = \left(\frac{V^+ - V_{CEsat} - V^-}{2v_{CL}} - 1\right) R_L$$

It follows that I_E is given by

$$I_E = \frac{V_X}{R_E} = \frac{V^+ - V_{CEsat} - V^-}{2R_E}$$

Example 2 *For the CC amplifier in Fig. 1, it is given that $R_S = 5\,\text{k}\Omega$, $R_1 = 120\,\text{k}\Omega$, $R_2 = 100\,\text{k}\Omega$, $R_E = 5.6\,\text{k}\Omega$, $R_L = 20\,\text{k}\Omega$, $V^+ = 15\,\text{V}$, $V^- = -15\,\text{V}$, $V_{BE} = 0.65\,\text{V}$, $\beta = 99$, $\alpha = 0.99$, $r_x = 20\,\Omega$, $V_A = 100\,\text{V}$ and $V_T = 0.025\,\text{V}$. Solve for v_O^+ and v_O^-.*

Solution. Because the dc bias circuits are the same as for the common-emitter amplifier example, the bias values are the same. It follows that the clipping levels are given by

$$v_O^+ = V^+ - V_{CEsat} - \left(V^- + I_E R_E\right) = 14.04\,\text{V}$$

$$v_O^- = -I_E R_E \| R_L = -9.25\,\text{V}$$

The value of I_E for symmetrical clipping is

$$I_E = \frac{V^+ - V_{CEsat} - V^-}{2R_E} = 2.66\,\text{mA}$$

To achieve this, either R_1, R_2, or both could be adjusted. The change in bias current would also change the small-signal gain. The new clipping levels are

$$v_O^+ = -v_O^- = I_E R_E \| R_L = 11.6\,\text{V}$$

Example 3 *The CC amplifier of Example 2 is required to clip symmetrically at the level $v_{CL} = 8\,\text{V}$ with the new load resistance $R_L = 3\,\text{k}\Omega$. Calculate the required values of R_E and I_E. If R_2 is held constant at the value $R_2 = 100\,\text{k}\Omega$, calculate the new value of R_1 to bias the transistor at the new current.*

Solution. The required voltage across R_E is $V_X = \left(V^+ - V_{CEsat} - V^-\right)/2 = 14.9\,\text{V}$. It follows that the new values for R_E and I_E are

$$R_E = \left(\frac{V_X}{v_{CL}} - 1\right) R_L = \left(\frac{14.9}{5} - 1\right) 3000 = 2.59\,\text{k}\Omega$$

$$I_E = \frac{V_X}{R_E} = 5.76\,\text{mA}$$

The new value of R_1 must satisfy

$$\left(\frac{V^+}{R_1} + \frac{V^-}{R_2} - \frac{I_E}{1+\beta}\right) R_1 \| R_2 = V^- + V_X + V_{BE}$$

This can be solved for R_1 to obtain $R_1 = 67.8\,\text{k}\Omega$.