Operational Amplifiers

Boosting Op-Amp Output Current

Abstract

Some applications require high output current from a precision operational amplifier (op-amp). Often, the op-amp can deliver this current, but not without sacrificing its precision performance. In this case, external transistor amplifiers can be added to boost the output current of the op-amp to the required level. While there is a wide variety of possible current amplifier options, this application note discusses the two most commonly applied solutions.

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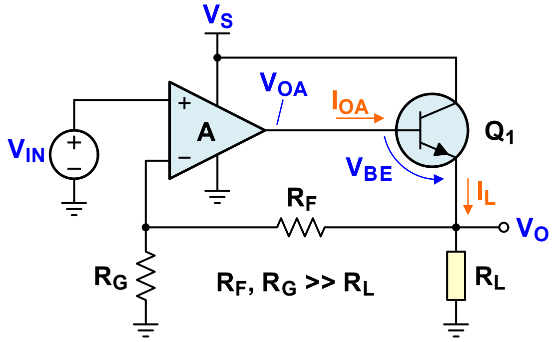
1. A Simple Transistor for Single-Supply Applications

For single supply applications, the simplest solution to increase the output current of the op-amp is using an NPN transistor, Q1. Both op-amp and transistor are powered from a common supply, V_S (Figure 1). You can also think of the circuit as an op-amp with integrated power transistor. In this circuit, the transistor is active all the time.



A = ISL28134
Q_1 = MMBT3904
$R_F = 90.9k\Omega$
$R_G = 10.1k\Omega$
$R_{Lmin} = 40\Omega$
$V_S = 5V$
V_{IN} = 0 to 0.4V
V_O = 0 to 4V

Figure 1. Increasing the Output Current of an Op-Amp with a Simple NPN Transistor

The op-amp operates as a non-inverting amplifier with the transistor as current booster. To prevent the feedback path from loading the circuit output, make R_F and R_G >> R_L. This results in the closed-loop voltage gain:

(EQ. 1) $$\frac{V_O}{V_{IN}} = 1 + \frac{R_F}{R_G} = \frac{1}{\beta}$$

with β as the feedback factor:

$$\beta = \frac{R_G}{R_G + R_F}$$

Due to op-amp action:

(EQ. 2) $$V_{IN} = I_L \cdot R_L \cdot \beta = V_O \cdot \beta$$

To maintain this linear relation, the output voltage of the op-amp (V_{OA}) must be larger than the output voltage of the circuit (V_O) by the amount of the base-emitter voltage (V_{BE}) necessary to turn on Q1.

(EQ. 3) $$V_{OA} = V_O + V_{BE}$$

Assuming a base-emitter voltage of $V_{BE} = 0.7V$ only holds true for small collector currents of a few mA. Higher collector currents of 50mA or 100mA increase V_{BE} to about 0.8V (Figure 2). V_{BE} increases even up to 0.9V, when considering operation at -40°C with the maximum collector current of the transistor at 100mA.

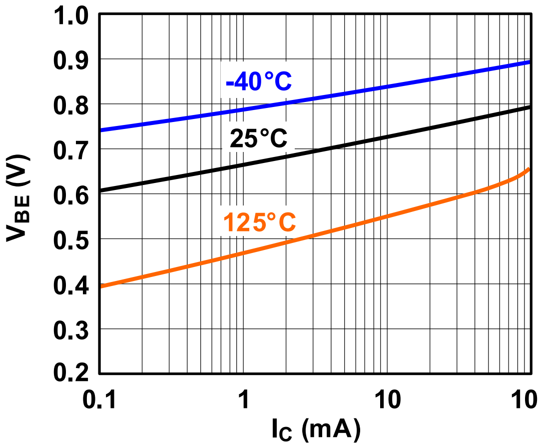


Figure 2. V_{BE} versus I_C

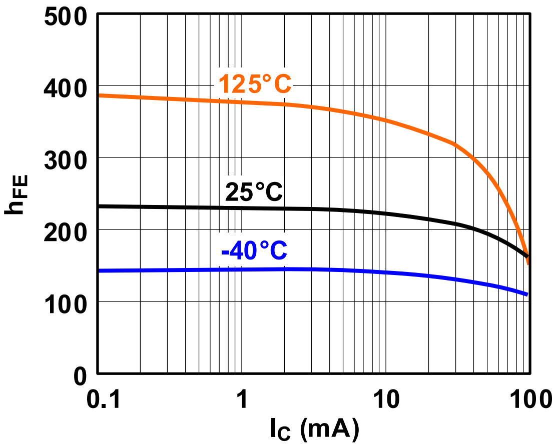


Figure 3. DC Current Gain, h_{FE}

Towards the upper end, V_{OA} is limited by V_S, provided that the op-amp is loaded with less than 1mA. Many general-purpose transistors, such as the popular MMBT3904 with 100mA maximum collector current, have a minimum current gain of $h_{FE} = I_C/I_B \geq 100$. This keeps their bias current, and therefore the op-amp output current, below 1mA (Figure 3). Nevertheless, to avoid output distortions, even for a rail-to-rail output, you might want to keep V_{OA} about 50mV below V_S.

(EQ. 4) $$V_{OA} = V_S - 0.05V$$

Setting Equation 4 equal to Equation 3 and solving for V_O gives:

(EQ. 5) $$V_O = V_S - 0.05V - V_{BE}$$

Applying the maximum V_{BE} of 0.9 results in the maximum possible output voltage of:

$$V_{Omax} = 5V - 0.05V - 0.9V = 4.05V \approx 4.0V$$

To ensure reliable operation with up to 100mA load current and down to -40°C, we settle for V_{Omax} = 4.0V. Then substituting V_O in Equation 2 with 4.0V makes:

(EQ. 6) $$V_{INmax} = I_L \bullet R_L \bullet \beta = V_{Omax} \bullet \beta = 4V \bullet \beta$$

In the above application, $\beta = R_G/(R_G + R_F) = 10.1k\Omega/(10.1k\Omega + 90.9k\Omega) = 0.1$, so that V_{INmax} = 0.4V.

Now, the V_{Omax} of 4V can be realized through various $I_L \cdot R_L$ combinations. V_{Omax} is therefore also known as the compliance voltage. For example, if neither the compliance voltage nor the maximum collector current of the transistor are exceeded, you can drive maximum 10mA into a 400Ω load, 40mA into a 100Ω load, or 100mA into a 40Ω load.

Figures 4 and 5 show the output current and voltage curves for a DC and a sinewave (1kHz) input. As can be seen in Figure 5, the output sinewave of the op-amp (V_{OA}) is distorted towards lower voltage levels. Negative feedback however, removes this distortion to present a true sinewave output across R_L.

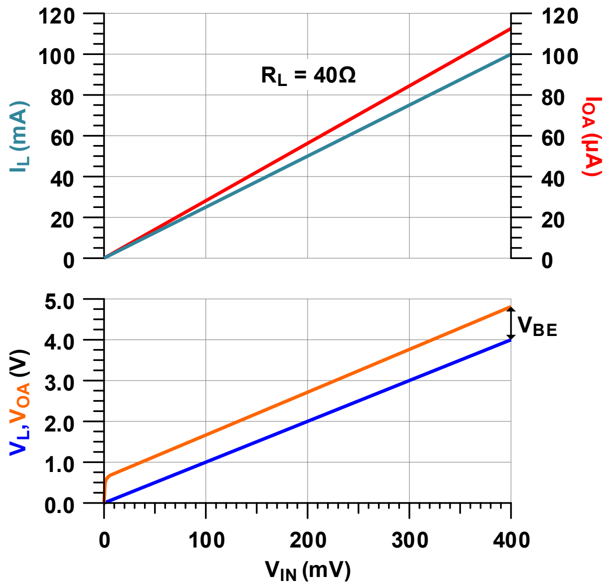


Figure 4. Output Currents and Voltages for a 0V to 0.4V DC Input Signal

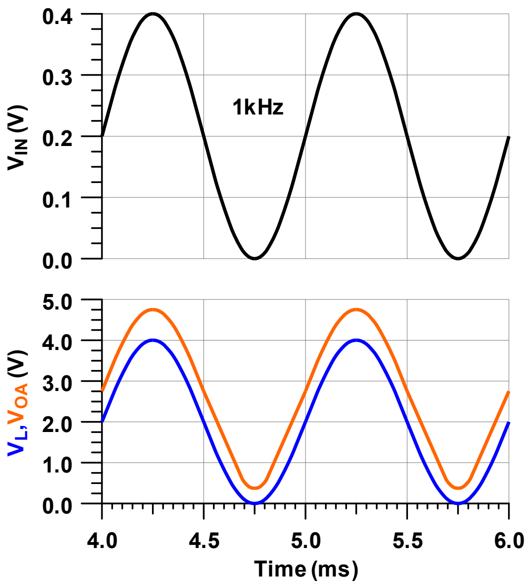
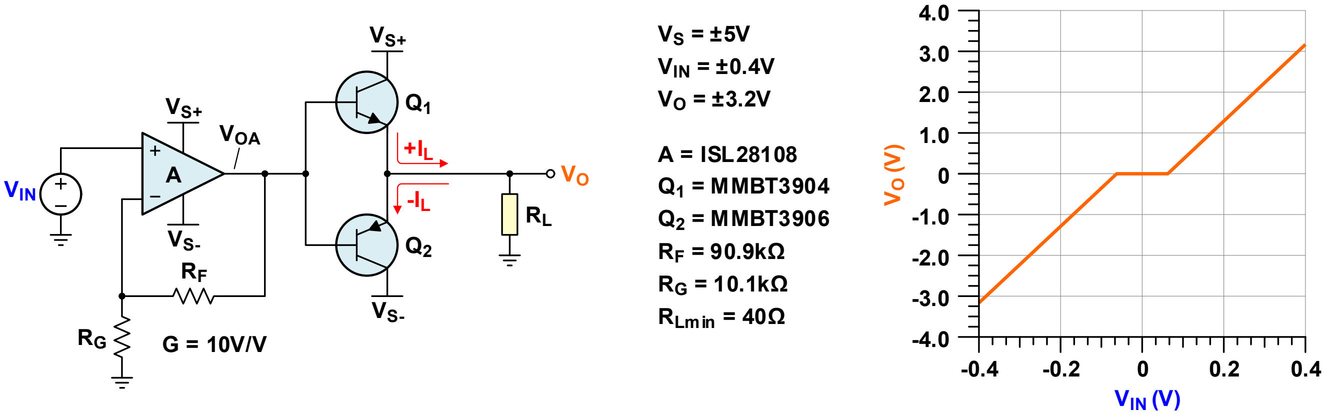


Figure 5. Output Currents and Voltages for a 0V to 0.4V 1kHz Sinewave Input Signal

2. Class-B Amplifier for Dual-Supply Applications

Dual supply applications require two transistors to boost the op-amp output current, an NPN for positive signals, and a PNP for negative signals. Figure 6 shows a current booster configuration without negative feedback from the circuit output. The signal source is a non-inverting amplifier with a gain of 10V/V, driving a pair of NPN and PNP transistors. For positive input signals, the NPN (Q1) sources current through the load, while the PNP (Q2) is turned off. For negative signals, the PNP sinks current from the load and the NPN is turned off. This operating mode is known as Class B mode.



$V_S = \pm 5V$
$V_{IN} = \pm 0.4V$
$V_O = \pm 3.2V$

A = ISL28108
Q_1 = MMBT3904
Q_2 = MMBT3906
$R_F = 90.9k\Omega$
$R_G = 10.1k\Omega$
$R_{Lmin} = 40\Omega$

Figure 6. Simple Class B Transistor Amplifier without Negative Feedback Showing Output Distortion

The drawback of a Class B amplifier without negative feedback is crossover distortion. This occurs at small input voltages, V_{IN}, where V_{OA} drops below the V_{BE} thresholds of both transistors. In this case, both transistors are turned off, and V_O assumes 0V.

The right diagram of Figure 6 depicts the behavior for a DC sweep of V_{IN}. Within the input voltage range of about $-65mV < V_{IN} < +65mV$, there is a dead band where V_O remains 0V. This dead band causes crossover distortion when applying a sinewave input (see also Figure 9).

The problem with the circuit in Figure 6 is that V_O is not a linear function of V_{IN}, but only the op-amp output is using: $V_{OA} = G \cdot V_{IN}$. At the same time, $V_{OA} = V_{BE} + V_O$. However, V_{BE} has a logarithmic relation to the collector current, which is also the load current (I_L): $V_{BE} = V_T \cdot \ln(I_L/I_S)$. Here I_S is the reverse saturation current of the transistors PN-junction, which is highly temperature-dependent. Then substituting V_{BE} with its logarithmic term, while expressing I_L through V_O/R_L, makes the output voltage:

(EQ. 7) $$V_O = V_{IN} \bullet G - V_T \bullet \ln\left(\frac{V_O}{I_S \bullet R_L}\right)$$

This is not a linear function, as V_O not only depends on I_S but also appears as an argument within the logarithmic term.

When moving the negative feedback from the op-amp output to the output of the Class B amplifier instead, V_O becomes linearly dependent on V_{IN} through $V_O \bullet \beta = V_{IN}$. If considering only positive input signals, the equations for the Class B amplifier are the same as for the simple transistor amplifier. V_{OA} is still the sum of V_{BE} and V_O and must not exceed the output saturation voltage (V_{OAsat}) of the op-amp. For the ISL28108 op-amp, V_{OAsat} is typically 50mV below V_{S+} for 1mA output current. Therefore, the maximum positive output voltage of our Class B amplifier is:

(EQ. 8) $$V_{O+max} = V_{OAsat} - V_{BEmax} = V_{S+} - 0.05V - V_{BEmax}$$

Using the same NPN and positive supply level as for the simple transistor amplifier, the values for V_{BEmax} (0.9V) and V_{S+} (5V) remain. This results in a maximum output voltage of $V_{O+max} \approx +4V$. Due to circuit and transistor symmetry, the same output magnitude is true for negative voltages, so that $V_{O-max} = -4V$.

For the Class B amplifier, the output compliance is, therefore, ±4V, which can be realized through various input voltage-times-gain products:

(EQ. 9) $$\pm V_{Omax} = \pm V_{IN} \bullet G$$

Figure 8 shows the final Class B amplifier circuit with negative feedback and its component list. The right diagram depicts the benefit of negative feedback, which results in the removal of the dead band during a DC sweep of V_{IN}, and the reduction in crossover distortion for sinewave inputs (Figure 9).

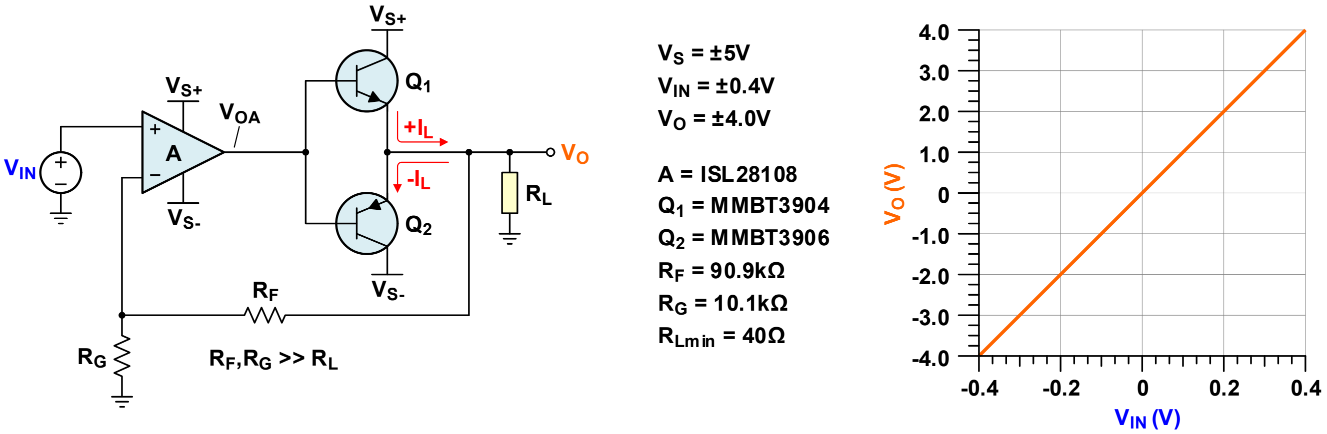


Figure 7. Class B Transistor Amplifier with Negative Feedback Shows no Dead Band During a DC Sweep of V_{IN}

Summarizing, Figure 8 depicts the crossover distortion of a 1kHz sinewave output of a Class B amplifier without negative feedback. Figure 9 shows that negative feedback greatly reduces crossover distortion of a 1kHz sinewave output, but does not remove it entirely, as depicted in the right diagram of Figure 9. When observing a small enough time window of ±1µs at about 5ms, a small crossover distortion still appears.

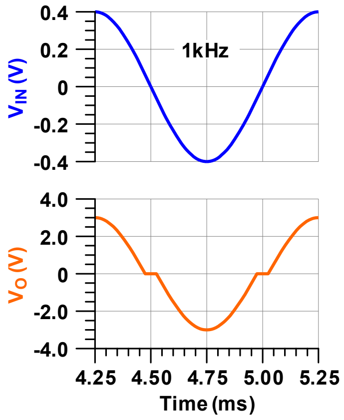


Figure 8. Class B Amplifier without Feedback Causing Crossover Distortion

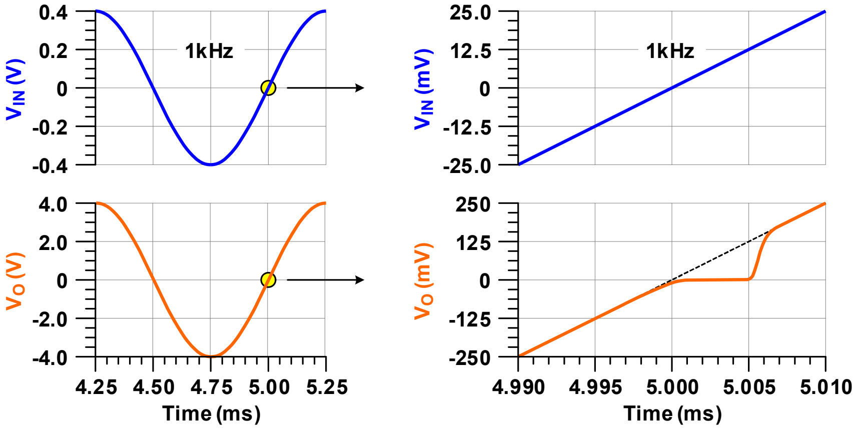


Figure 9. Class B Amplifier with Negative Feedback Greatly Reduces Crossover Distortion but does not Eliminate It

Note: The amount of remaining crossover distortion depends on the loop-gain of the circuit at the signal frequency. The higher the loop-gain, the smaller the distortion. Because loop-gain is the difference between closed-loop and open-loop gain, the following are various options to increase the loop gain:

- Operating the circuit at unity-gain
- Limiting your signal to lower frequencies
- Using an op-amp with a high open-loop gain

All of the above are reasons why the Class B amplifier current booster is limited to DC and low-frequency applications.

3. Revision History

Rev.	Date	Description
1.00	Jul.2.20	Initial release

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