

## 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.

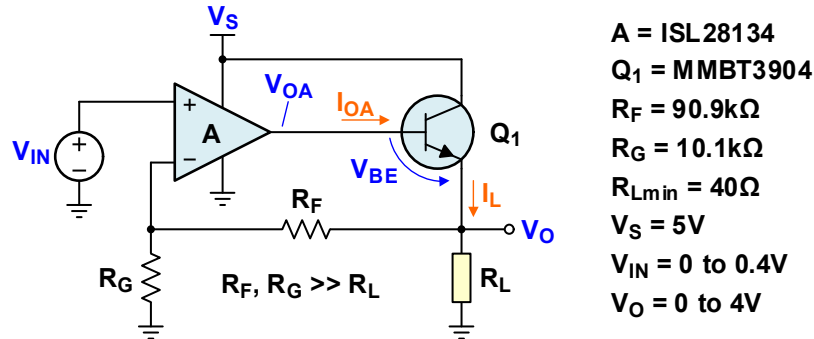


Figure 1. Increasing the Output Current of an Op-Amp with a Simple NPN Transistor

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  $R_G \gg R_L$ . This results in the closed-loop voltage gain:

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

with  $\beta$  as the feedback factor:

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

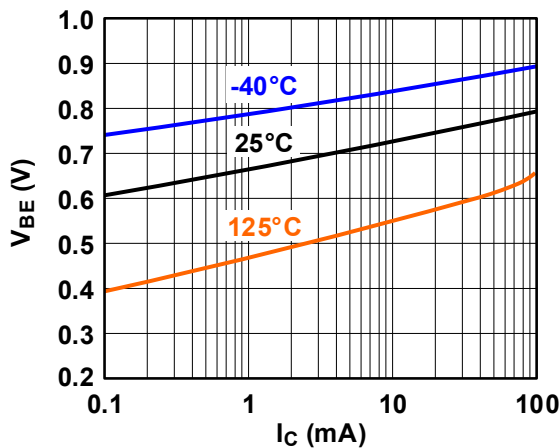
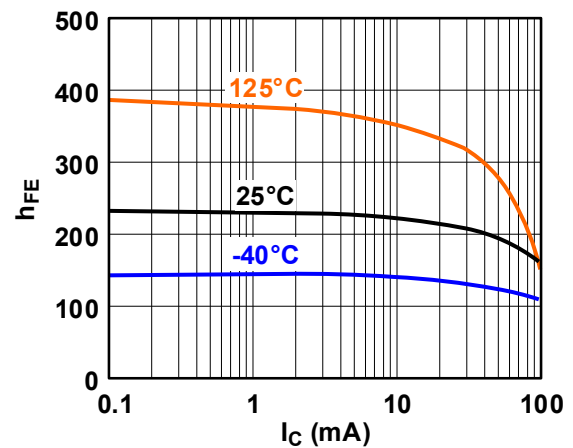
Due to op-amp action:

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

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.

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

Assuming a base-emitter voltage of  $V_{BE} = 0.7\text{V}$  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  $-40^\circ\text{C}$  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  $V_S$ .

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

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

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

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  $-40^\circ\text{C}$ , we settle for  $V_{Omax} = 4.0V$ . Then substituting  $V_O$  in Equation 2 with 4.0V makes:

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

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 400 $\Omega$  load, 40mA into a 100 $\Omega$  load, or 100mA into a 40 $\Omega$  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  $R_L$ .

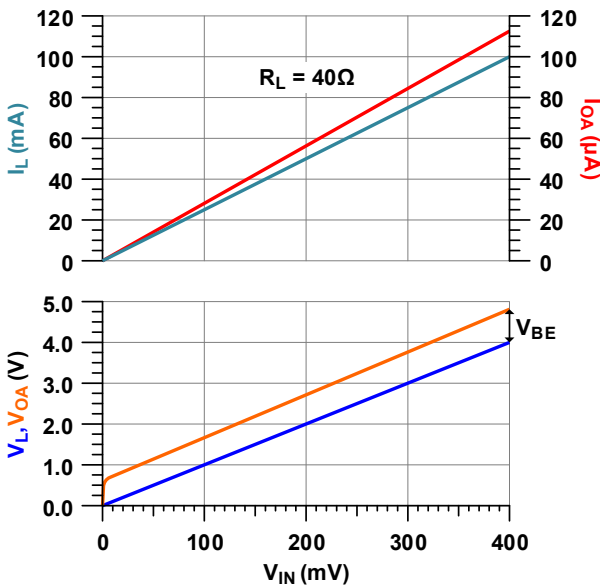


Figure 4. Output Currents and Voltages for a 0V to 0.4V DC Input Signal

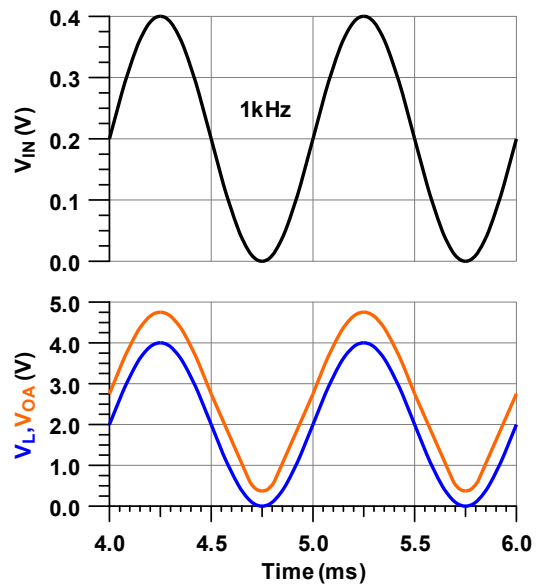


Figure 5. Output Currents and Voltages for a 0V to 0.4V 1kHz Sinewave Input Signal

## 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.

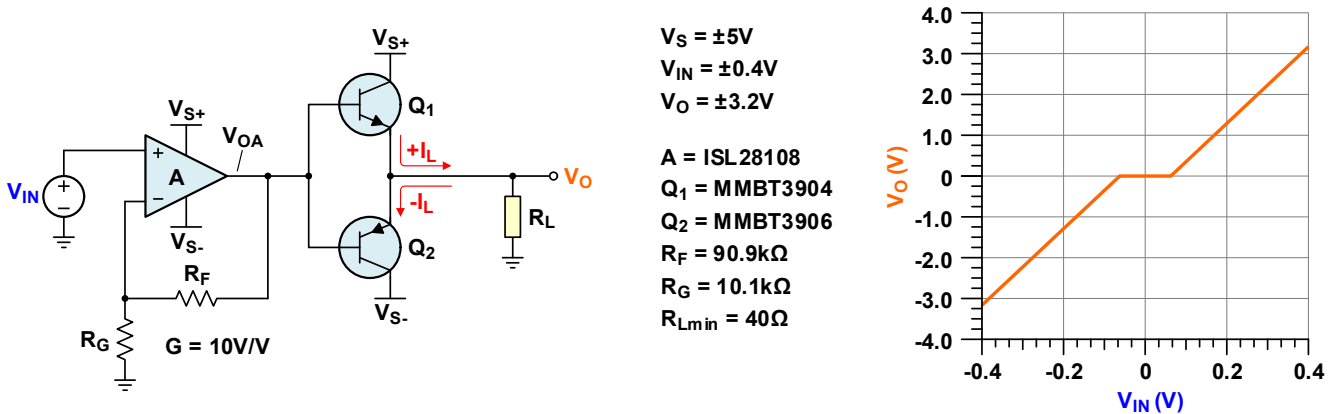


Figure 6. Simple Class B Transistor Amplifier without Negative Feedback Showing Output Distortion

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:

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

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  $V_O \cdot \beta = V_{IN}$ . 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:

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

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,  $\pm 4V$ , which can be realized through various input voltage-times-gain products:

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

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).

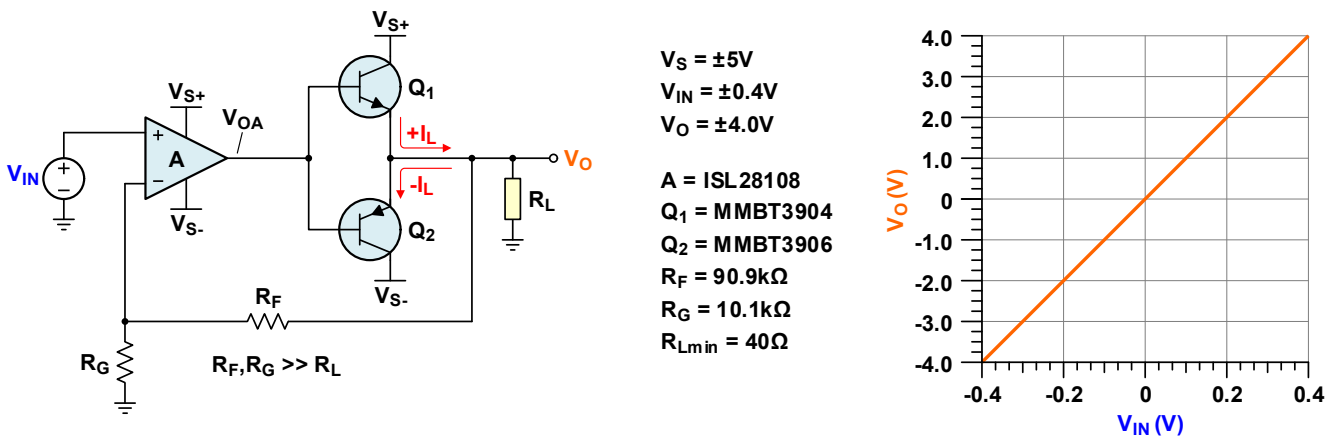
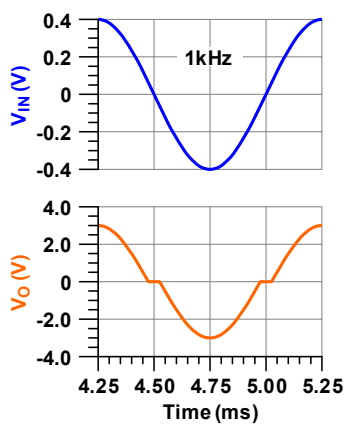
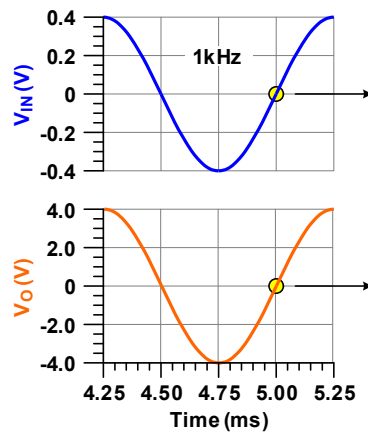


Figure 7. Class B Transistor Amplifier with Negative Feedback Shows no Dead Band During a DC Sweep of  $V_{IN}$

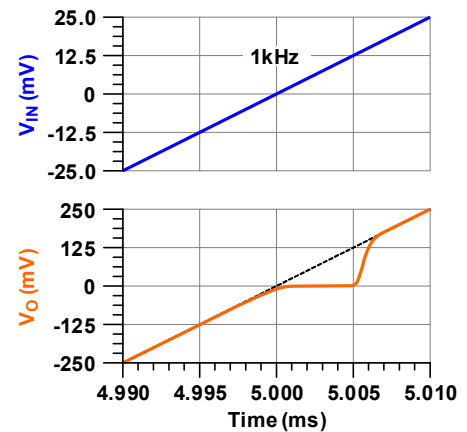
Summarizing, Figure 8 depicts the crossover distortion of a 1kHz sinewave output of a Class B amplifier without negative feedback. Figure 9 shows that negative feedback greatly reduces crossover distortion of a 1kHz sinewave output, but does not remove it entirely, as depicted in the right diagram of Figure 9. When observing a small enough time window of  $\pm 1\mu s$  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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