What does 'rail to rail' output operation really mean?

Bonnie Baker - January 22, 2013

The advertisements for single-supply operational amplifiers often claim rail-to-rail output capability. What does this assertion really mean? Page one of a single-supply op amp’s data sheet may call out “rail-to-rail input/output swing” in the title or bullets; read on, because if you are looking for a single-supply amplifier whose output can be driven all the way to one supply rail and/or the other, good luck. So, what should you know about an amplifier’s performance that claims rail-to-rail output operation?

Two amplifier specifications will help you sort out this problem: output-voltage swing and open-loop voltage gain.

The output-voltage swing of an op amp defines how far you can drive the amplifier output toward the positive or negative supply rail. The output-voltage-swing high ($V_{OH}$) and output-voltage-swing low ($V_{OL}$) test conditions usually take the amplifier outside its linear region. The amplifier’s open-loop-voltage-gain ($A_{VOL}$) specification primarily is the ratio of the closed-loop, output-voltage change to the input-offset-voltage change, but it also provides output-linearity hints in the test conditions.

The $V_{OH}$ and $V_{OL}$ specifications tell us how close the output pin comes to the power-supply rails. Figure 1 shows a single-supply amplifier’s output behavior. The output stage’s transistors prevent the amplifier from reaching either rail.
Figure 1 The output signal ramping from $V_{SS}$ (GND) to the positive power supply ($V_{DD}=5V$) never reaches either rail. At ground, the amplifier stops at $\sim11 \text{ mV}$ from the rail; at $V_{DD}$, the amplifier stops at $\sim5 \text{ mV}$ from the rail.

As you examine these specifications with respect to their test conditions, you will find that the amplifier’s output swing is dependent on the amount of current that the output stage is driving into the load. As you can see in Table 1 (Amplifier A), the defined conditions of this specification have a significant influence on the amplifier’s output performance. As the table shows, $V_{OH}$ is the difference between VDD (positive supply). $V_{OL}$ is the difference between the minimum voltage out and $V_{SS}$ (negative supply).

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Condition ($V_{DD}=5V, V_{SS}=\text{GND}$)</th>
<th>Result (mV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$V_{OH}$</td>
<td>with 10-kΩ load to $V_{DD}/2$</td>
<td>11.2</td>
</tr>
<tr>
<td>$V_{OH}$</td>
<td>with 10-kΩ load to $V_{SS}$</td>
<td>1.95</td>
</tr>
<tr>
<td>$V_{OL}$</td>
<td>with 10-kΩ load to $V_{DD}/2$</td>
<td>11.6</td>
</tr>
<tr>
<td>$V_{OL}$</td>
<td>with 10-kΩ load to $V_{SS}$</td>
<td>3.7</td>
</tr>
</tbody>
</table>

The key to comparing $V_{OH}$ and $V_{OL}$ from amplifier to amplifier is to determine the sink or source current. Smaller output currents provide better output-swing performance.

$V_{OH}$ and $V_{OL}$ tell us how close the amplifier drives to the rails but do not imply that the amplifier is linear so close to the supply voltage rails; the conditions of the $A_{VOL}$ specification, by contrast, do. Measure $A_{VOL}$ by comparing the amplifier’s output swing in its linear region with the amplifier’s input offset voltage. The dc open-loop gain is equal to the following equation:

$$A_{VOL} = 20 \log \left( \frac{\Delta V_{OUT}}{\Delta V_{OS}} \right),$$

where $\Delta V_{OUT}$ is the dc change in output voltage and $\Delta V_{OS}$ is the dc change in input offset voltage.

Table 2 (Amplifier B) shows an example of the $A_{VOL}$ specifications and test conditions for a single-supply amplifier. In the condition column, note that the high and low output ranges of the amplifier are 5 mV from the power supplies. The $A_{VOL}$ specification verifies that the amplifier is in its linear region.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Condition</th>
<th>Min</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>$A_{VOL}$</td>
<td>$R_L=100 \text{ kΩ}$, $(V_{SS})+5 \text{ mV}&lt;V_o&lt;(V_{DD})-5 \text{ mV}$</td>
<td>100</td>
<td>dB</td>
</tr>
<tr>
<td>$A_{VOL}$</td>
<td>$R_L=2 \text{ kΩ}$, $(V_{SS})+5 \text{ mV}&lt;V_o&lt;(V_{DD})-5 \text{ mV}$</td>
<td>96</td>
<td>dB</td>
</tr>
</tbody>
</table>

If you are looking at a single-supply op amp that’s claimed to offer rail-to-rail operation, make sure you look deeper before using the product in your application. Consider the $V_{OH}$, $V_{OL}$, and $A_{VOL}$ specifications and conditions. Doing so will keep you from wasting your time and will ensure that you have the correct amplifier for your circuit.

Also see:
What does "rail to rail" input operation really mean?
Rail-to-rail input amplifier application solutions
Are you violating your op amp's input-common-mode range?
Single-supply amplifier outputs don't swing rail to rail
Wisely using rail-to-rail op amps