What Does "Rail-to-Rail" Operation Really Mean?

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A hot topic with single-supply operational amplifiers is whether they have rail-to-rail input or output operation capability. While some amplifiers on the market are able to accept input voltages from one rail to the other rail, this is achieved with a few compromises in performance. Single-supply amplifier manufacturers also claim they have devices that will swing rail-to-rail on the output. With these types of amplifiers, the output cannot go all the way to the rails, though it can get close. This Analog Design Note briefly shows the actual performance of some of the more popular single-supply amplifiers.

Rail-to-Rail Operation on the Input

The input voltage range is a function of the input circuit topology. There are three basic topologies that are used to design the input stage of single-supply, voltage-feedback amplifiers. The most common topology has a single differential input stage using PMOS as the first transistors at the input terminals. With this topology, the gate of both transistors go as low as 0.2V (or 0.3V) below the negative power supply voltage while still remaining in their linear active region. At the positive rail, these transistors must remain well below the positive power supply voltage. An amplifier designed with a PMOS input stage will typically have an input range of $V_{SS} - 0.2V$ to $V_{DD} - 1.2V$.

An amplifier with a NMOS input differential pair is not as common as an amplifier with a PMOS input differential pair. In this configuration, the input range is restricted to 1.2V above the negative rail, though it is capable of ranging above the positive rail (by a few tenths of a volt) while still remaining in the linear region of the amplifier.

A third topology for the input stage of single-supply amplifiers uses parallel PMOS and NMOS differential input stages. This topology combines the advantages of both stages to achieve actual rail-to-rail input performance. When the input terminals of the amplifier are driven towards the negative rail, the PMOS transistors are turned completely on while the NMOS transistors are completely off. When the input terminals are driven to the positive rail, the NMOS transistors are in use while the PMOS transistors are off. Between these two extremes, both input stages are on to varying degrees. The best way to view this behavior is to look at the offset voltage versus the common mode input voltage, as shown in Figure 1.

Rail-to-Rail Output Performance

The output swing of an op amp defines how close the output of the amplifier can be driven to the negative or positive supply rail under defined operating and load conditions. Unfortunately, the voltage output swing specifications of amplifiers are not standardized from manufacturer to manufacturer. There are two approaches to defining output voltage swing. With the first approach, the output current determines how close the output can go to the rail
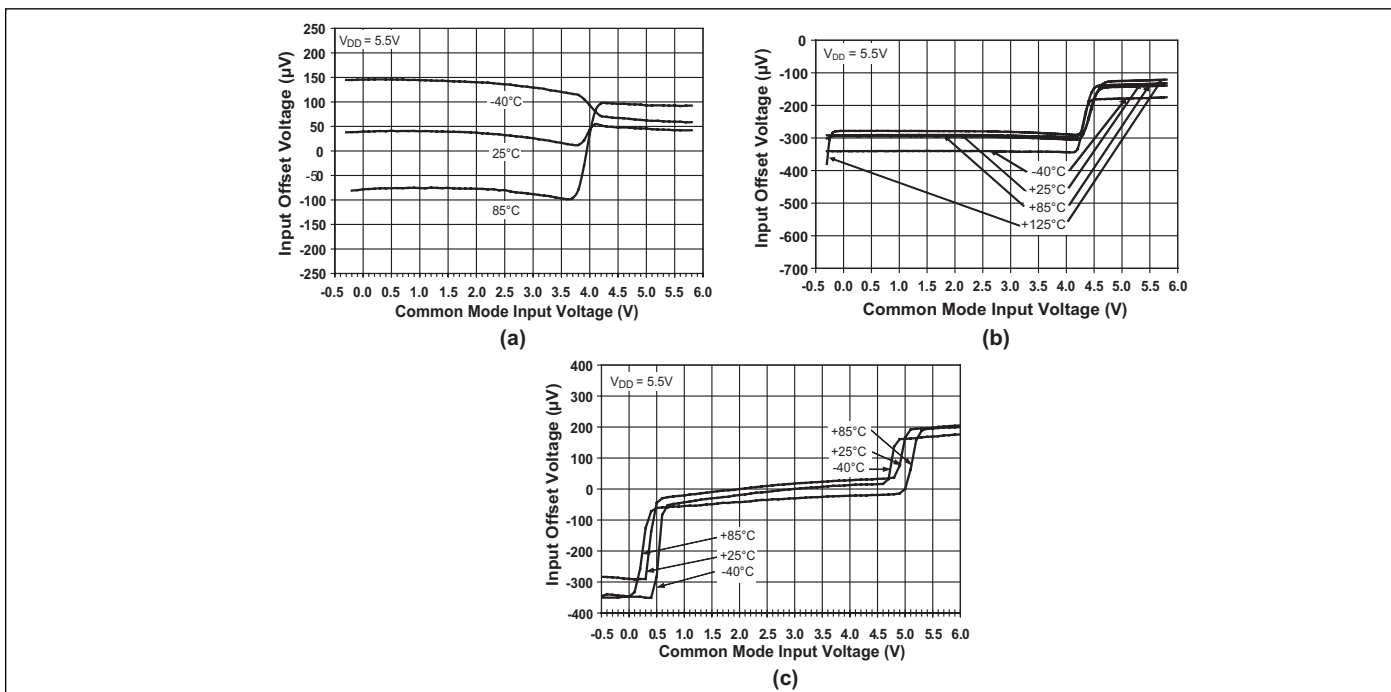

Figure 1. *As the common mode voltage of the amplifier changes from ground to the positive supply, the input stage of the MCP6021 (a) changes from its PMOS input pair to its NMOS input pair at approximately 1.5V below the positive supply rail. The input stage of the MCP6001 (b) changes from its PMOS input pair to its NMOS input pair at approximately 1V below the positive supply. The input stage of the MCP6041 (c) changes from its PMOS input pair to both input pairs at approximately 0.5V above ground and to the NMOS input pair at approximately 0.75V below the positive rail.*

(V_{OH} and V_{OL}). This is the most common specification. The second method is to use the amplifier's open-loop gain specification (A_{OL}). A_{OL} is defined over a smaller output swing. This smaller output range is usually several hundred millivolts from the rails (instead of tens of millivolts) and is related to the linear output voltage range of the amplifier.

With the first approach, an amplifier's output swing is dependent on the amount of current that the output stage is driving under test, with the output voltage defined as Voltage-out Low (V_{OL}) and Voltage-out High (V_{OH}). With this specification, care should be taken when comparing amplifiers. For instance, a single-supply amplifier (MCP601) is used to generate the data in Table 1. As is shown in this table, the defined conditions of this specification have a significant influence on the amplifier's performance.

The key to comparing V_{OL} and V_{OH} from amplifier to amplifier is to determine the output sink or source current. Smaller output currents will provide better output swing performance, as shown in Table 1. If the load is referenced to $(V_{DD} - V_{SS})/2 + V_{SS}$, the output current is determined by dividing the voltage across the load resistor by that resistance. When the load is referenced to $(V_{DD} - V_{SS})/2 + V_{SS}$, the output of the amplifier will be sourcing or sinking half the current, as when the load is referenced to V_{DD} or V_{SS}.

For instance, in the first row of Table 1, assume that V_{DD} is equal to 5V and V_{SS} is equal to 0V. Given these conditions, the amount of current coming from the amplifier into to the load is equal to:

$$\text{Load Current} = ((V_{DD} - V_{SS})/2 + V_{SS})/RL$$
$$= ((5V - 0V)/2 + 0V)/10 \text{ k}\Omega$$
$$= 250 \text{ μA}$$

The device in Table 1 was tested with V_{DD} equal to 5V and V_{SS} equal to ground. Since this data was taken with one device, it does not necessarily represent the performance of all devices in the product family.

Although this performance specification will tell you how close the amplifier will drive to the rails, it will not describe the linear region of the device. However, using the open-loop gain (A_{OL}) of an amplifier will provide the second approach to defining the output swing of that amplifier. A_{OL} is measured by comparing the output swing of the amplifier in its linear region to the input offset voltage of the amplifier. The DC open-loop gain is calculated as:

$$A_{OL} = 20*\log (\Delta V_{OUT}/\Delta V_{OS})$$

Where:

ΔV_{OUT} is the DC change in output voltage, and

ΔV_{OS} is the DC change in input offset voltage.

Conclusion

If you are looking at a single-supply, rail-to-rail operational amplifier, be sure to do some investigating before using the product in your application. While one manufacturer may claim rail-to-rail output operation based on the operational amplifier's good performance in applications where the output goes to the power supply rails (such as in clamping circuits or comparator circuits, V_{OL} and V_{OH} are optimized), a different manufacturer may mean that the op amp will perform linearly across the entire output range (A_{OL} is optimized). Microchip supports both perspectives, where the amplifier maximum output swing (V_{OL} and V_{OH}) is specified as "Output Voltage Swing" and the linearity of the amplifier with respect to output swing is supported in their A_{OL} specification.

References:

AN722 - "Operational Amplifier Topologies and DC Specifications", Baker, Bonnie C., Microchip Technology Inc.

Output Voltage Swing	Test Conditions	Measured Output Swing from V_{SS} (V_{OL}, mV)	Measured Output Swing from V_{DD} (V_{OH}, mV)
High, to V_{DD}	w/10 kΩ load referenced to $(V_{DD} – V_{SS})/2 + V_{SS}$	—	11.2
High, to V_{DD}	w/10 kΩ load referenced to V_{SS}	—	20.4
High, to V_{DD}	w/10 kΩ load referenced to V_{DD}	—	1.95
High, to V_{DD}	w/amplifier source current equal to 100 μA	—	3.8
Low, to V_{SS}	w/10 kΩ load referenced to $(V_{DD} – V_{SS})/2 + V_{SS}$	11.6	—
Low, to V_{SS}	w/10 kΩ load referenced to V_{SS}	3.7	—
Low, to V_{SS}	w/10 kΩ load referenced to V_{DD}	25.5	—
Low, to V_{SS}	w/amplifier sink current equal to 100 μA	8.1	—

Table 1. *This data was taken with one sample of the MCP601 op amp and demonstrates the effects of the output conditions on the output swing performance of that amplifier. This data was taken with no regard to the open-loop gain of the amplifier.*

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