Operational Amplifiers Part II of VI
Working With Single-Supply Op Amp Characteristics

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Single-supply operational amplifier advertisements often claim rail-to-rail output operation capability. But, what does this claim really mean? If you are looking for this type of amplifier, you should first recognize that there are very few on the market today that can actually operate to the rails. So, what should you know about the performance of amplifiers that claim rail-to-rail output operation? If it appears that the output swing capability of the amplifier will be a problem, a second look at the amplifier will be productive. Better yet, a third look may be needed, because this specification may or may not provide the information you need. This article will show the actual performance of some of the more popular single-supply amplifiers along with tips on how to use them.

Amplifier output stages have changed. In the past they required a standard ±15-V power-supply voltage. With single-supply amplifiers, the supply voltage has gone down dramatically and the negative supply is now ground. Typically, single-supply amplifiers are required to operate using a 5V-supply or lower. Since power supply voltages have reduced, the output range of the amplifiers has also changed. The output swing of a single-supply amplifier is required to swing rail-to-rail or as close as possible.

What Does the R-R Output Specification Mean? -- Single-supply amplifier manufacturers claim they have devices with rail-to-rail swing capability. In its simplest form, the output swing specification of a single-supply op amp defines how close the output signal can be driven to the negative or positive supplies. Furthermore, the output swing is dependent on the amount of output loading. This definition states how high or low the amplifier output stage can go. It does not imply that the operational amplifier is operating in its linear region as the output approaches the extremes. The output swing test condition is specified in a variety of ways, as shown in Table 1.

Example #	Parameter	Conditions (V_{DD} = 5 V, V_{SS} = gnd)	Test Results
1a	V_{OH}	w/ 10 kO load referenced to $V_{DD}/2$	V_{OH} = 11.2 mV
1b	V_{OH}	w/ 10 kO load referenced to V_{SS}	V_{OH} = 20.4 mV
1c	V_{OH}	w/ 10 kO load referenced to V_{DD}	V_{OH} = 1.95 mV
1d	V_{OH}	w/ amp source current equal to 100 µA	V_{OH} = 3.8 mV
2a	V_{OL}	w/ 10 kO load referenced to $V_{DD}/2$	V_{OL} = 11.6 mV
2b	V_{OL}	w/ 10 kO load referenced to V_{SS}	V_{OL} = 3.7 mV
2c	V_{OL}	w/ 10 kO load referenced to V_{DD}	V_{OL} = 25.5 mV
2d	V_{OL}	w/ amp sink current equal to 100 µA	V_{OL} = 8.1 mV

Table 1: Manufacturers State Test Conditions For Output Voltage Swing In A Variety Of Ways: V_{OH} Is Difference Between V_{DD} And Maximum Voltage Out (High Output Swing); V_{OL} Is Difference Between Minimum Voltage Out And Ground (Low-Output Swing); V_{DD} Is Positive Supply, V_{SS} Is Negative Supply

The diversity of the conditions in Table 1 makes it difficult to compare one amplifier to another. But, these conditions have one thing in common: the amplifier output current. Although the output current is specifically stated in case 1d and 2d it is easy to calculate the current in the other cases by subtracting the output voltage from the load reference voltage. For instance in case 1a, the amplifier is sourcing ((V_{DD} – V_{OH}) – V_{DD}/2) ÷ 10 kO = 249 µA ~ 250 µA. For case 1b, the amplifier is sourcing twice the current as compared to case 1a.

The effect of these conditions is shown in the last column of Table 1. This test data was taken using one sample. The conditions outlined in 1c and 2b make the amplifier look pretty good. If you calculate the sink or source current, you will quickly discover that the amplifier is driving near zero microamperes.

Is the Amplifier Still an Amplifier? -- This is not the only specification that describes the operation of the output stage: it only defines how far the amplifier can swing. What is not stated is what happens to the rest of the amplifier. In reality, if an amplifier is pushed to the rails the offset voltage of the amplifier will dramatically change.

The output swing Vs. offset voltage of a typical amplifier is shown in Fig. 1. It is noticeable that the linearity of the amplifier starts to degrade long before the output swing reaches the supply voltages. If the output of an amplifier is operated beyond the linear region of this curve, the input-to-output relationship of the signal will be nonlinear.

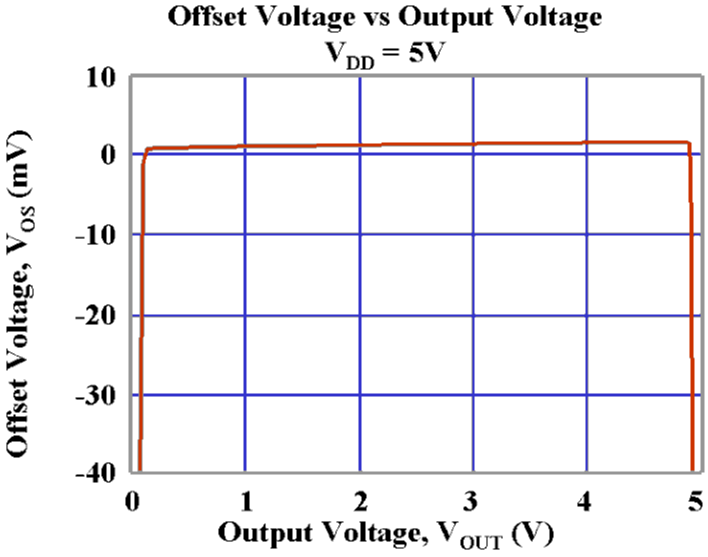


Fig. 1: As Amplifier Output Swing Goes Towards The Rail Amplifier Functionality Eventually Breaks Down, Manifested By Changes In Input Offset Voltage

The open-loop gain (A_{OL}) specification can be used to determine the linear range of the amplifier. The definition of the open-loop gain of an amplifier is:

A_{OL} (dB) = 20 log (? V_{OUT} ÷ ? V_{OS})

Where, V_{OUT} is the output voltage, V_{OS} is the input offset voltage, ? V_{OUT} is (V_{OH} – V_{OL}), and ? V_{OS} is the change in offset voltage given the change in output voltage.

The open-loop gain test is performed with two stated conditions; 1.) Output-swing range and 2.) Output load.

The difference between the A_{OL} conditions and the output swing conditions are very different. The A_{OL} specification implies that the operational amplifier is operating within its linear region. Examples of this specification are shown in Table 2.

Vendor	Output Swing Conditions	V_{OH} (max)	V_{OL} (max)	Open Loop Gain Conditions	A_{OL} (max)
A	I_{OH} = 100 µA	150 mV		R_L = 50 kO to $V_{DD}/2$ V_{OUT} = 1 V to 4 V	98 dB
	I_{OL} = 100 µA		150 mV		
B	R_L = 25 kO to $V_{DD}/2$, A_{OL} > 90 dB	100 mV		R_L = 25 kO to $V_{DD}/2$ V_{OUT} = 100 mV to 4.9 V	90 dB
	R_L = 25 kO to $V_{DD}/2$, A_{OL} > 90 dB		100 mV		
C	R_L = 10 kO to $V_{DD}/2$	20 mV		V_{DD} = +15 V V_{OUT} = 2.5 V to 12.5 V	114 dB
	R_L = 10 kO to $V_{DD}/2$		20 mV		

Table 2: Each Manufacturer Has Its Own Way Of Stating Output Swing And Open-Loop Gain Conditions: V_{OH} Is Difference Between V_{DD} And Maximum Voltage Out (High Output Swing); V_{OL} Is Difference Between Minimum Voltage Out And Ground (Low-Output Swing); V_{DD} = 5 V, V_{SS} = Ground, Unless Otherwise Specified

From Table 2, manufacturer A has different conditions between the amplifier output swing and open-loop gain specifications. In this example, the amplifier drives 30 µA when testing the open-loop gain, but the output swing conditions call out 100 µA load currents. This amplifier cannot be in its linear region, while driving the V_{OH} and V_{OL} limits. Although this amplifier has been advertised as having “rail-to-rail output” performance, these specifications would indicate that this particular amplifier could only drive the inputs of a 12-bit ADC between the ranges of 1 V to 4 V.

The conditions and specifications given by manufacturer B (Table 2, again) are more conservative. With this device, the output swing conditions and open-loop gain conditions are the same. This amplifier could drive the inputs of a 12-bit ADC between the ranges of 100 mV to 4.9 V, while achieving good linearity.

Manufacturer C has stated its specifications in the best light possible. The output-swing test demonstrates good rail-to-rail operation at a load of ~250 µA. The 20 mV specification for V_{OH} and V_{OL} is the best of the three amplifiers. The open-loop gain specification is also the best of the three. However, when the conditions are carefully inspected, you can see that the amplifier is tested across its most stable and linear region. This is done with extended power-supply voltages. The output-voltage swings 2.5 V from the rail. The question one would ask is, “ Would this amplifier be able to drive a 12-bit ADC in a zero- to 5-V single supply environment?” It’s hard to say.

Applications Challenge -- These range restrictions become critical in a subset of amplifier applications. One example would be where the amplifier is driving the input of an ADC.

Digital conversion counts at the edges of the output-swing range of an amplifier will be lost. In some cases the loss of a few hundred counts is tolerable. In other cases, the loss of the full-scale range near ground and the power supply may be an issue.

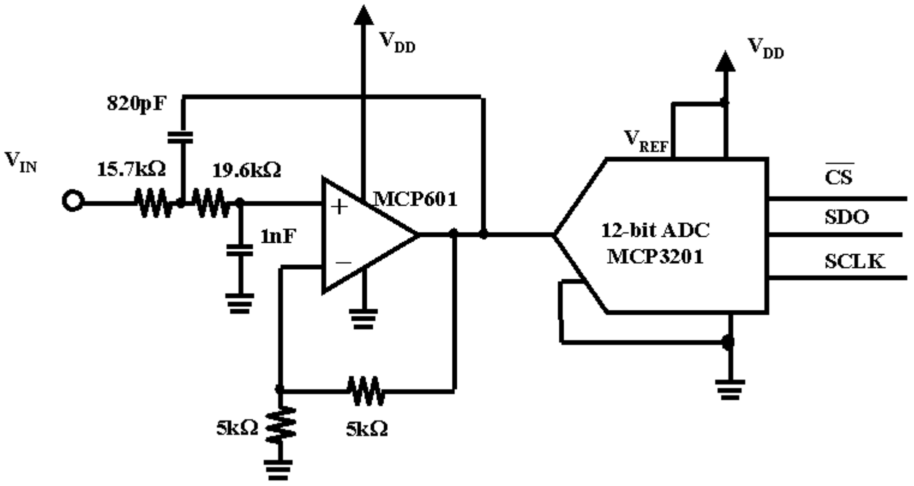
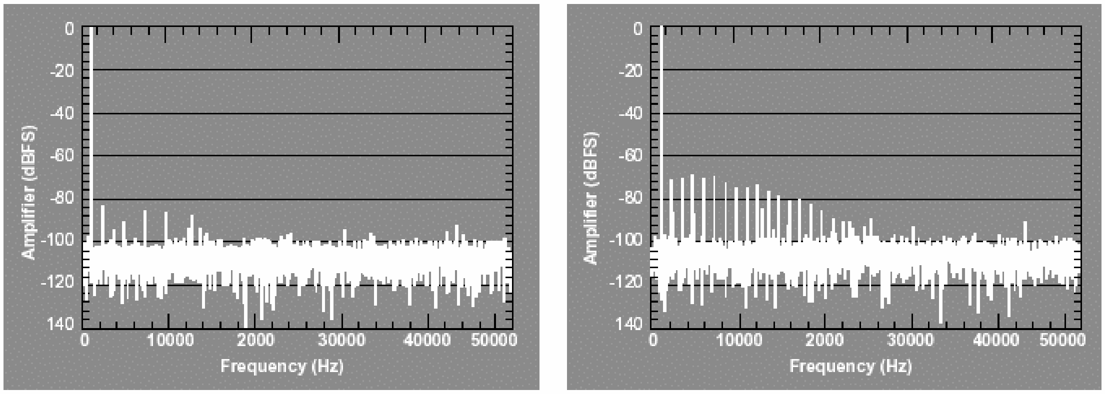


Fig. 2: 2.8-MHz CMOS Amplifier Using Full Output Swing, Configured Gain Of 2 V/V As 2^{nd}-Order Low-Pass Filter To Remove Alias Noise Driving 12-Bit SAR ADC

A good circuit example to describe this issue is in Fig. 2 where the input signal is injected into the non-inverting input of the amplifier. The amplifier is configured as a 2^{nd}-order, 10-kHz, low-pass filter in a gain of 2 V/V. The op amp (MCP601) has a 2.8-MHz gain-bandwidth product. This amplifier then drives a 12-bit ADC that is capable of sample speeds up to 100 ksample/s over temperature. The power-supply voltage for both products is 5 V and the reference voltage to the ADC is also 5 V, with 1 LSB equivalent to 1.22 mV. Op-amp swing is limited from ground and to $V_{DD,}$ illustrated in Fig. 3.



(a) Output Peak-to-Peak of Op Amp = 4.456V

(b) Output Peak-to-Peak of Op Amp = 4.72V

Fig. 3: Circuit In Fig. 2 Converts Input Signal At 1 kHz Sampled At 100 ksample/s

The data in Fig. 3 show two FFT (fast Fourier transform) responses of one op amp and one 12-bit ADC, generated using an amplifier input signal of 1 kHz and an ADC sampling rate 100 ksample/s.

The difference between the data in these graphs is generated by the output stage of the amplifier. In Fig. 3a the amplifier-output swing is 4.456 V peak-to-peak, which can be described as an output swing from 272 mV to 4.728 , equivalent to an ADC output data range of 223 to 3875 from 4096 possible codes; the FFT data is the same as the performance of the ADC alone.

The scenario in Fig. 3b is different with the data collected using the same amplifier and ADC with an amplifier output signal of 4.72 V peak-to-peak, or 140 mV to 4.86 V. This is equivalent to an ADC output-data range of 115 to 3984 from 4096 possible codes. The resulting data illustrate how the amplifier is unable to produce an undistorted 1-kHz signal. As can be seen the fundamental appears as well as 16+ harmonics. The attenuation above the 10th harmonic is caused by the amplifier's low-pass filter.

What does Rail-to-rail Output Really Mean? -- If an advertisement claims rail-to-rail op amp output operation, make sure you look deeper before using the product for your application. Rail-to-rail output really means something different to every op amp manufacturer. For one manufacturer it may mean that the op amp will perform well in applications where the output needs to go to the power-supply rails, such as clamping circuits or comparator circuits. For another manufacturer it may mean that the op amp will perform linearly across the entire output range. Until op amp manufacturers settle on one standard the challenge for the system designer is to pay close attention to all of these specifications, as well as their conditions.

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