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APPLICATION NOTE 4428

Rail-to-Rail: Railroading and the Electronics of Op Amps

By: Bill Laumeister, Strategic Applications Engineer
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Abstract: Railroads have had rail-to-rail components for years that were, in fact, nearly rail to rail. Op amps employ the same nearly rail-to-rail tradition. This application note discusses rail-to-rail op amps, and explains why some inputs and outputs can be less than, nearly, or slightly more than the power rails.

Introduction

For some, rail travel conjures up nostalgic images. They look at an old train engine and it represents a time and lifestyle from a bygone era. It suggests a simpler, slower time. That image is nothing like today's commute or even air travel. Most business trips today are done on the run. Sadly, waiting in airport security lines is about the only time that we are not racing around.

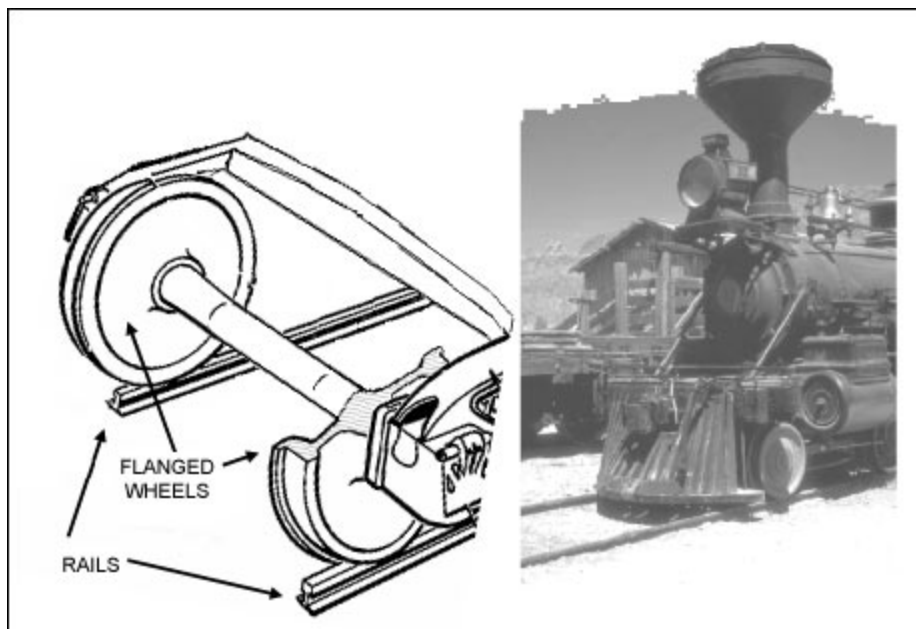


Figure 1. Railroad use of "rail-to-rail" flanged wheels.

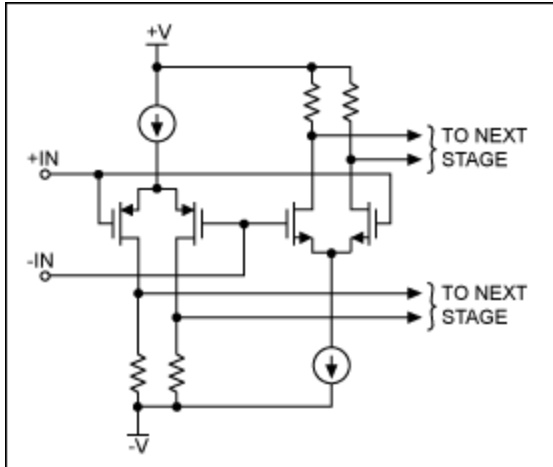


Figure 3. A MOS rail-to-rail input stage.

As with most engineering there are trade-offs in performance among devices. Temperature stability, input impedance, frequency response, and offset currents vary across the different transistor families. This means that the choice of transistor is application dependent.¹

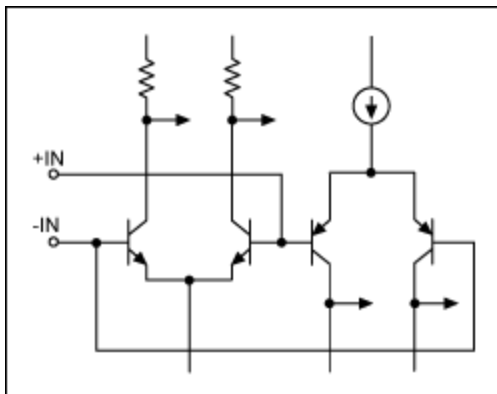


Figure 4. Bipolar op amp input stage.

In Figures 3 and 4 the "P" input pair will be active near the most negative power-supply limit. The "N" input pair will be active near the most positive power-supply limit. Somewhere in the center of the operating range, the signal must transition from one pair to the other. At the transition, distortion will rise and the input currents will change between the pairs (**Figure 5**). This is illustrated in the case of the [MAX4122](#). As the common-mode input voltage of the rail-to-rail input amplifier sweeps from one supply rail to the other, the input bias current changes both in sign and in magnitude. Much of the modern IC technology is centered on reducing the distortion and balancing the currents.

Unlike other rail-to-rail op amps, in the [MAX4091](#) family of op amps the transition region has been widened to approximately 600mV to minimize the slight degradation in CMRR caused by this mismatch. A careful study of the data sheet is important to understand these issues. In low-voltage, low-current op amps it is not uncommon to see both a warning about the crossover distortion, and a recommendation to bias a sensitive signal to avoid the crossover point.

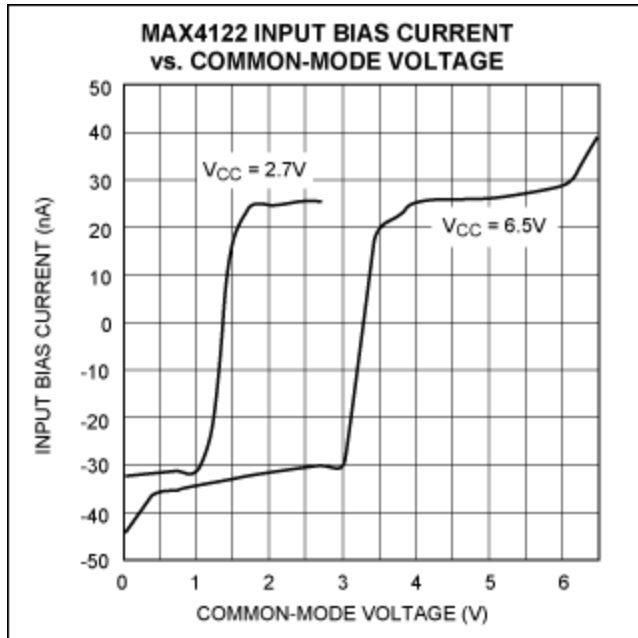


Figure 5. Bias change in a rail-to-rail input stage for the MAX4122 op amp.

Even though the MAX4091 op-amp family is made with a bipolar process, the input bias currents are typically less than 20nA. Since the bias current flows into the device when the NPN input stage is active and flows out when the PNP input stage is active, it is necessary to consider the effects of that current. To reduce the offset error caused by input bias current flowing through external source resistances, those impedances should be well matched. The data sheet discusses this in detail.

There is another important feature to look for in an op-amp data sheet, a statement similar to the following: there is no phase reversal or latchup for overdriven inputs. Both were a common problem in early op amps and they raise havoc in most circuits. Some latchup conditions even resulted in destroying the devices.

With typical rail-to-rail op amps like the MAX4091 family, the input common-mode range extends 50mV beyond the positive and negative supply rails. This range has evolved to 100mV beyond the positive and negative supply rails for the MAX9910 family. Further improvement resulted in the development of the proprietary Beyond-the-Rails technology in the MAX4220 and MAX4091 families. These latter devices can extend 200mV beyond the positive and negative supply rails.

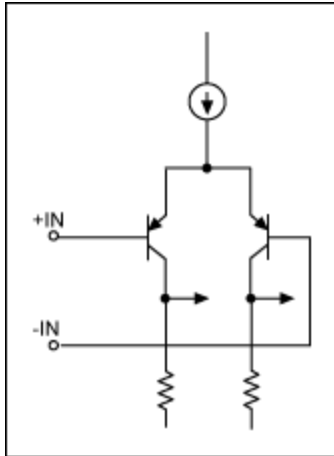


Figure 6. Input circuit which includes a ground in the input range.

Figure 6 shows the typical bipolar configuration of an op amp that includes the ground rail in the common-mode range. Bipolar parts which exhibit this negative-rail capability are the [MAX4493](#) and [LMX321](#) families. CMOS-equivalent parts are the [MAX4475](#) and [MAX4036](#) families.

Rail-to-Rail Outputs

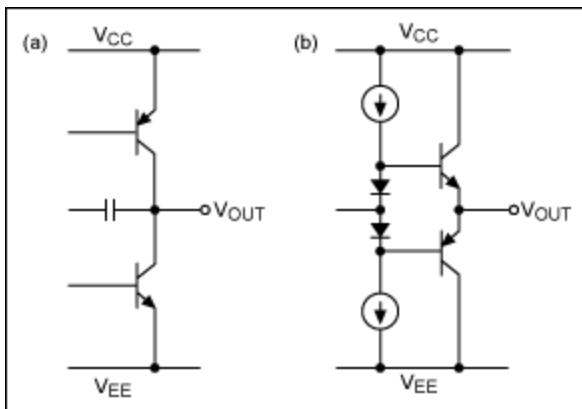


Figure 7. A rail-to-rail output stage (a) and the standard output stage (b).

Like the railroad wheel flanges that go almost rail to rail, the output circuits of op amps go almost rail to rail. The crucial data-sheet information about this is a statement that says the output voltage swings to within "n" mV of the supplies with an "n" Ω load.

A rail-to-rail output stage (**Figure 7a**) has a common-emitter configuration, while a standard output stage (**Figure 7b**) has an emitter-follower configuration. Watch the data sheet load condition. One might expect the load to be connected to ground, but often the load is connected to one-half of the power-supply values. The rail-to-rail output specifications are always with light loading. As the load (current) increases, the amplifier is less able to swing near the rails. Therefore, if a low-distortion large current is required at a voltage near the power-supply amplitude (rail), one must consider increasing the power-supply voltage and use a conventional op amp. An alternative is to use the [MAX4162](#) op-amp family, which takes a novel approach to the problems of the standard rail-to-rail output stage. These op amps have a classic emitter-follower output stage, but achieve rail-to-rail outputs with an internal charge-pump converter that provides internal supply voltages to bias several amplifier stages, including the output stage. Thus, the input stage has a standard ground-sensing configuration, but allows inputs to swing from ground to

V_{CC2}. As is always true, the application dictates the best circuit configuration.

Summary

Rail-to-rail op amps have a range of typical output swings for various devices. A typical output swing for the MAX4091 family is to within 15mV of the supplies with a 100kΩ load. When connected as a voltage-follower, the MAX4321's output swings from 0.02V to 2.97V with a +3V supply and with a 100kΩ load to ground. For the MAX4321 the maximum output-voltage swing depends on the load, but will be within 300mV of a +5V supply, even with the maximum load of 250Ω to ground. When connected as a voltage-follower, the MAX4230 is guaranteed to be within 500mV of the positive rail (V_{DD} = 2.7V) even with maximum load of 32Ω to ground. The output stage for the MAX4240–MAX4244 can drive up to a 10kΩ load and still swing to within 40mV of the rails. Thus the application helps define the proper part.

Traveling by rail is nostalgic and the rail-to-rail flanged wheels are still guiding trains. With op amps, we have seen that "rail to rail" for inputs can even mean Beyond the Rails. For outputs, just like the railroad, it can mean *almost* rail to rail. Likely op amps will continue to improve as technology advances, and because of their benefits they will be used for many years.

References

1. Maxim application note 741, "[Rail-to-Rail Outputs and Beyond-the-Rails Inputs: The Inside Story on Micropower Op Amps.](#)"
2. Maxim application note 656, "[Design Trade-Offs for Single-Supply Op Amps.](#)"

Beyond-the-Rails is a trademark of Maxim Integrated Products, Inc.

Related Parts		
LMX321	Single/Dual/Quad, General-Purpose, Low-Voltage, Rail-to-Rail Output Op Amps	Free Samples
MAX4036	Low I _{BIAS} , +1.4V/800nA, Rail-to-Rail Op Amps with +1.2V Buffered Reference	Free Samples
MAX4091	Single/Dual/Quad, Micropower, Single-Supply, Rail-to-Rail Op Amps	Free Samples
MAX4122	Single/Dual/Quad, Wide-Bandwidth, Low-Power, Single-Supply Rail-to-Rail I/O Op Amps	Free Samples
MAX4162	SOT23, Micropower, Single-Supply, Rail-to-Rail I/O Op Amps	Free Samples
MAX4220	Miniature, 300MHz, Single-Supply, Rail-to-Rail Op Amps with Enable	Free Samples
MAX4475	SOT23, Low-Noise, Low-Distortion, Wide-Band, Rail-to-Rail Op Amps	Free Samples
MAX4493	SC70, Low-Power, General-Purpose, Dual-Supply, Rail-	Free Samples

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