



[Rail-to-rail input amplifier application solutions](#)

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Many single-supply operational amplifiers are capable of rail-to-rail input operation, if they have the proper input circuitry to support this function. This article is an expansion of the blog post [“What does ‘rail to rail’ input operation really mean?”](#) By examining an additional input-stage topology and implementing these op amps into some common op-amp circuits, you will see what I mean.

The article discusses a composite input-stage topology for single-supply op amps. You may recall that this topology exhibited an offset-voltage, crossover distortion as the input common-mode voltage traveled across the full rail-to-rail input voltage range. Switching from one differential input stage to the other causes this distortion.

Revisiting single-supply input topologies

The CMRR (common-mode rejection ratio) specification describes changes in the amplifier’s offset-voltage versus common-mode input changes. The specification conditions can subtly describe the amplifier’s rail-to-rail input topology. A typical common-mode rejection specification for an amplifier with a composite input stage has two or more CMRR specifications (**Table 1**).

Input Voltage Range		Conditions	Min	Typ	Max	Units
Common-Mode Voltage Range	V_{CM}		-0.3		(V+) +0.3	V
Common-Mode Rejection Ratio	CMRR	$-0.3 < V_{CM} < (V+) - 1.8\text{ V}$	80	92		dB
		$V_S = 5\text{ V}, -0.3\text{ V} < V_{CM} < 5.3\text{ V}$	70	84		dB
		$V_S = 2.7\text{ V}, -0.3\text{ V} < V_{CM} < 3\text{ V}$	66	80		dB

Table 1 The single-supply op-amp data sheet describes the CMRR test conditions as well as the actual specified values. These specification tables provide evidence of the characteristics of the input-stage topology, which in this case is an amplifier with a composite input stage.

In **Table 1**, the CMRR is equal to $20 \cdot \log(\Delta V_{CM}/V_{OS})$. Line 1 verifies that the amplifier has true rail-to-rail input capability. Line 2 specifies the CMRR from ground to 1.8V below the positive power-supply rail as 92 dB (typ). Note that this specification does not describe the range specified in Line 1. Line 3 specifies the CMRR across the entire input range as 70 dB (typ, $V_S=5\text{V}$). This disparity in specification only points out that the amplifier’s input stage has a composite input topology.

There are more ways to tackle this input topology problem with the IC design. The composite input stage is one example. As a second IC-design strategy, a unique zero-crossover input topology provides superior common-mode performance over the entire input range.

In **Figure 1**, a regulated charge pump lifts the top of the differential input as well as its biasing

current source to 1.8V above the power-supply voltage, V_S . This increased headroom allows for a single differential PMOS input stage to replace the composite differential input stage. A typical common-mode rejection specification for an amplifier with a charge-pump input stage has one CMRR specification. This specification encompasses the full amplifier input range.

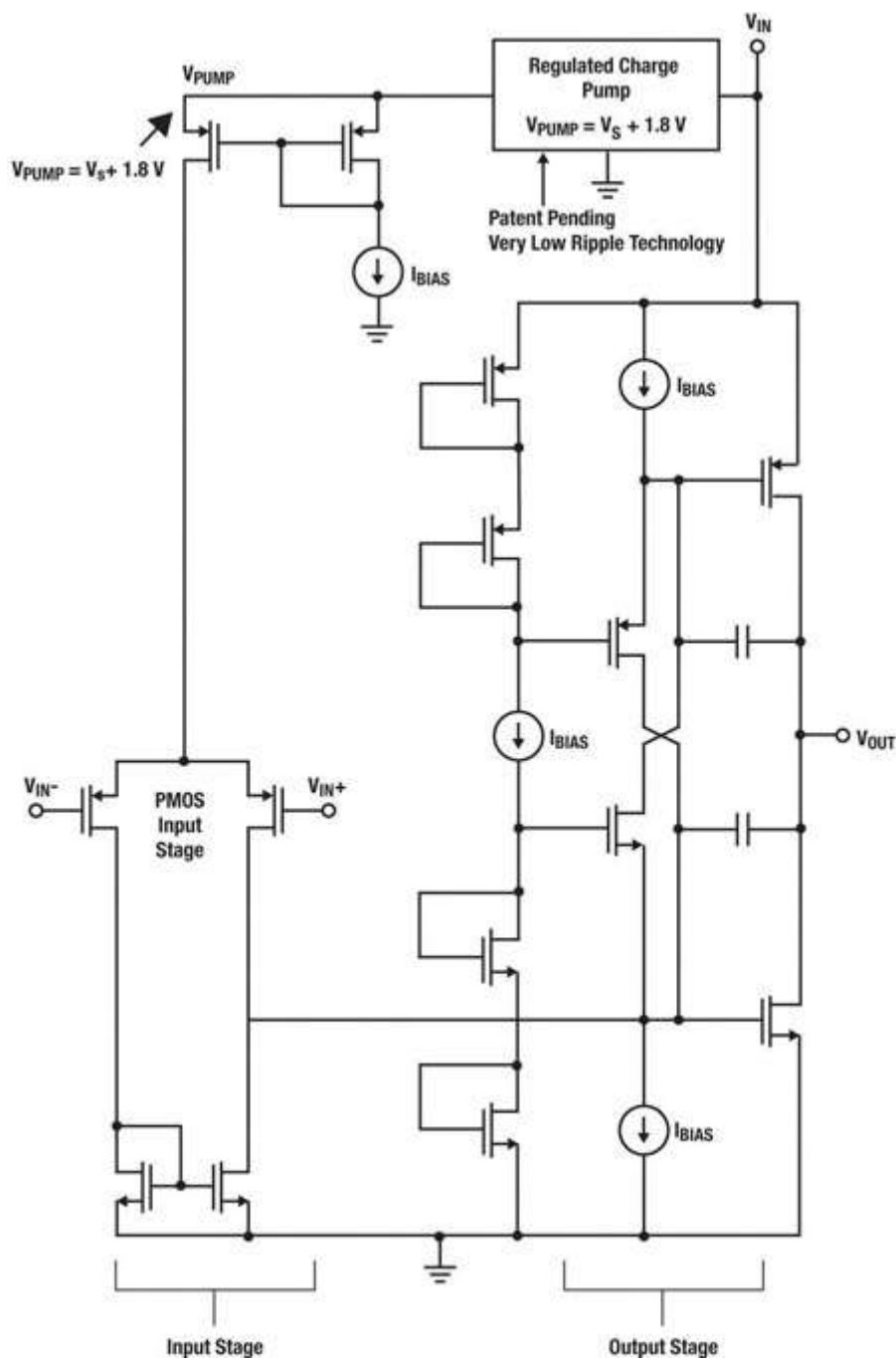


Figure 1 This single PMOS differential input stage in conjunction with a high-side charge-pump eliminates the common-mode crossover distortion found in composite input stages.

Figure 2 compares the response of the charge pump to composite amplifier inputs. The difference between these two topologies in this **figure** is obvious.

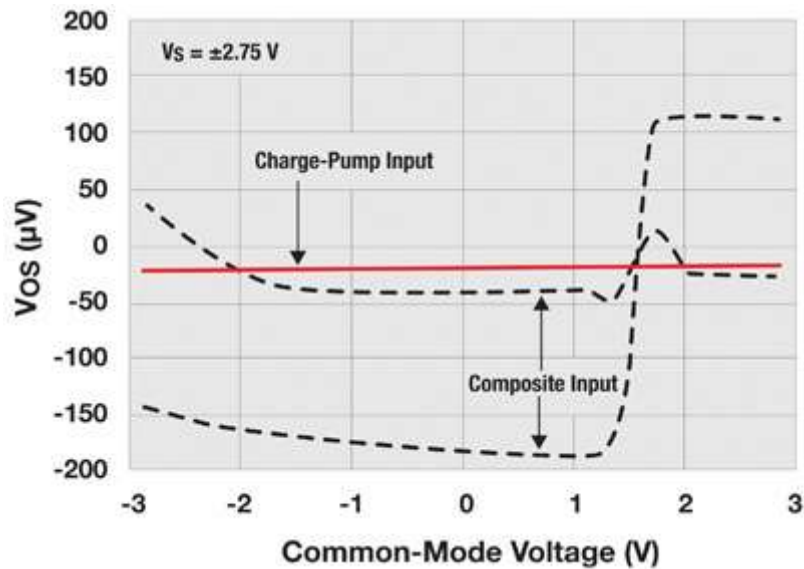


Figure 2 The op-amp offset voltage of an op amp with a charge-pump input remains constant across changes in the common-mode voltage. The offset voltage of an op amp with a composite input varies across changes in the common-mode voltage.

The op-amp topology in **Figure 1** provides superior common-mode performance over the entire input range. In fact, the input range extends at least 100 mV beyond both power-supply rails. You may think that the charge pump's output ripple voltage will become a noise problem. However, the charge-pump design can provide an output ripple voltage that is low enough so as to not produce undesirable noise or distortion at the output of the op amp.

Application solutions

Circuit designers can use rail-to-rail input op amps in virtually any op-amp configuration. To achieve optimum performance, however, circuit designers need to consider the behavior of the single-supply op-amp input stage. Let's consider the behavior of the composite and charge-pump amplifier inputs in a single-supply inverting amplifier, noninverting amplifier, and buffer circuits.

In many applications, the amplifier's common-mode input voltage can remain at a static voltage. This is true for the inverting-amplifier circuit found in **Figure 3**. The inverting-amplifier circuit gains the input signal as well as changes the signal polarity.

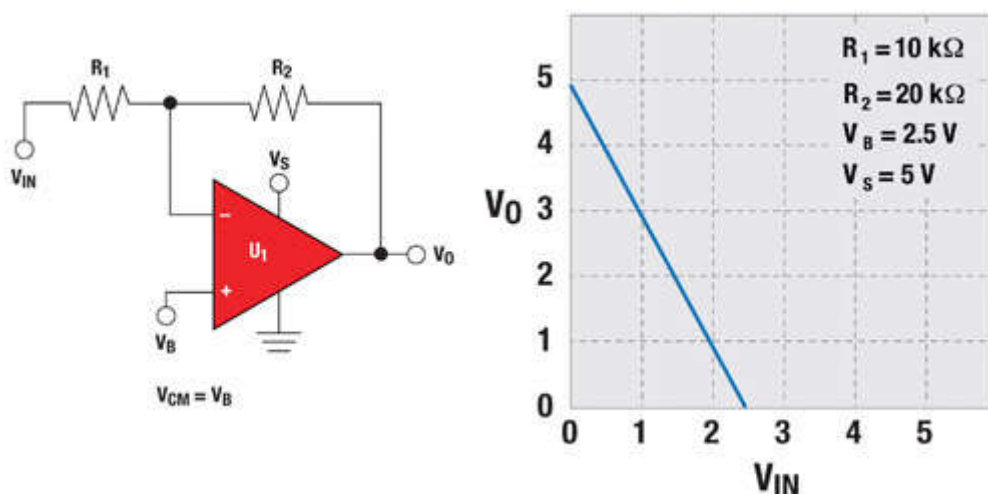


Figure 3 The inverting-amplifier circuit keeps the amplifier's common-mode voltage at a constant voltage, V_B .

The circuit requires a bias voltage, V_B , to keep the output range at V_O between the power-supply rails. When V_B establishes the common-mode voltage of the amplifier, the transfer function for this circuit is expressed as

$$V_O = V_{IN} \frac{R_2}{R_1} + V_B \frac{R_1 + R_2}{R_1}$$

The V_B voltage can be anywhere between ground and V_S , as long as the combination of the elements in this circuit (V_B , R_1 , R_2 , and V_{IN}) keeps the output (V_O) between V_S and ground. Since the V_B voltage is static, the amplifier's common-mode voltage remains constant. When using composite input amplifiers, choose the V_B voltage to be below or above the PMOS/NMOS transition region. **Bottom line: inverting-amplifier circuit**

Bottom line: inverting-amplifier circuit

- **Composite input:** performs without distortion with V_B outside the PMOS/NMOS transition region
- **Charge-pump input:** performs without distortion

The noninverting amplifier's common-mode voltage (**Figure 4**) is equal to the input voltage, V_{IN} . The noninverting amplifier circuit gains the input signal with a voltage level-shift implemented with V_B .

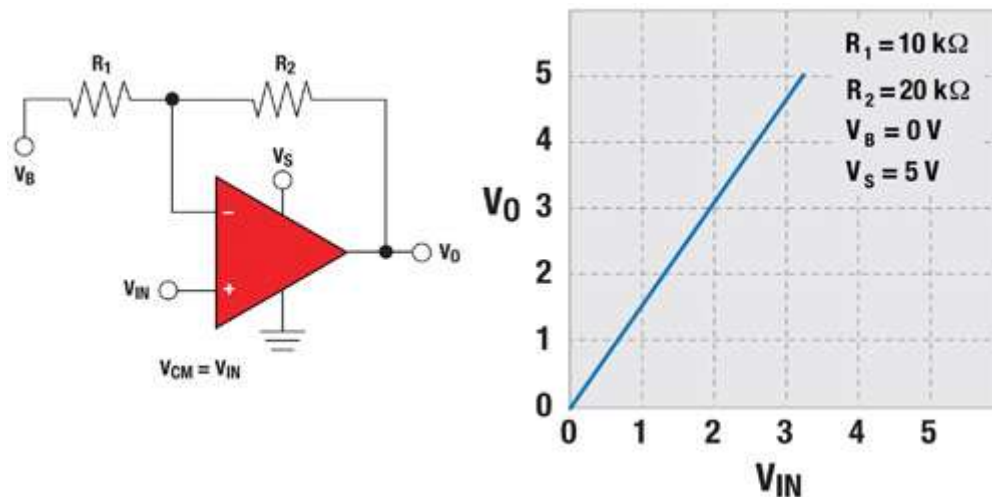


Figure 4 The noninverting gained amplifier configuration allows the amplifier's common-mode voltage to change with input signals.

For proper operation, the noninverting amplifier circuit may require a bias voltage, V_B , to keep the output range at V_O between the power-supply rails. Here V_B establishes the common-mode voltage of the amplifier. The transfer function for the circuit is expressed as

$$V_{OUT} = V_{IN} \frac{R_2 + R_1}{R_2} + V_B \frac{R_2}{R_1}$$

The input common-mode voltage (V_{IN}) can vary between ground and V_S , as long the voltage at V_O remains between the power-supply rails. V_B can be assigned so that the input signal is not required to go across the composite input stage's crossover region. If the input signal always remains less or more than the composite input-stage's transition voltage, the circuit will not create distortion from the composite's input stage, crossover phenomena.

Bottom line: noninverting-amplifier circuit

- **Composite input:** the input signal (V_{IN}) must not travel into the transition region of the PMOS and CMOS differential input stages
- **Charge-pump input:** performs without distortion in reaction to common-mode voltage or V_{IN} changes

With a unity-gain buffer (**Figure 5**), the input signal (V_{IN}) can traverse from one rail to the other rail. In this circuit, V_{IN} establishes the amplifier's common-mode voltage. If the circuit designer uses the amplifier in a voltage follower or buffer configuration, the composite amplifier exhibits some limitations in linearity due to the input-stage topology. If the circuit designer wants a distortion-free output from this amplifier circuit, an op amp with a composite input topology may limit the input range of the buffer.

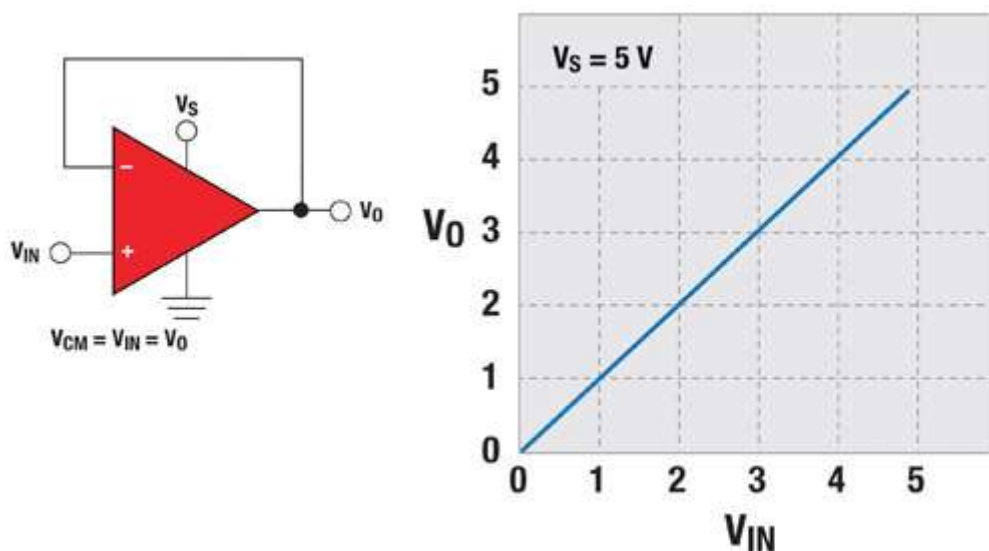


Figure 5 The input signal, V_{IN} , of the buffer circuit changes the amplifier's common-mode voltage. Composite input op amps can create distortion at the output, V_O , as V_{IN} changes.

The transfer function of the circuit in **Figure 5** is shown here:

$$V_O = V_{IN}$$

The input common-mode voltage (V_{IN}) can vary between power-supply rails. If V_{IN} travels across this entire range, the composite input amplifier produces distortion at the circuit output, V_O . If the input signal always remains less than the composite input stage's transition voltage, the circuit does not create distortion from the composite's input stage, crossover phenomena. Alternatively, an amplifier with a charge-pump input stage does not create this unwanted distortion across the entire input range.

Bottom line: buffer circuit

- **Composite input:** the op amp's input range (V_{IN}) must not travel into the transition region between the PMOS and CMOS differential input stages
- **Charge-pump input:** performs without distortion in reaction to common-mode voltage changes

Conclusion

Manufacturers use several input topologies in their designs of rail-to-rail input amplifiers. It is true that circuit designers can use rail-to-rail input amplifiers in virtually any op-amp configuration. However, if you choose to use a rail-to-rail input amplifier, it pays to understand the CMRR impact on your circuit. The composite input amplifier produces a crossover distortion, requiring special considerations in some classes of circuits. The charge-pump input amplifier does not produce this same distortion.

References

1. Edgar Sánchez-Sinencio, "[Rail-to-Rail Op Amps](#)," Ax-09, TAMU, AMSC
2. Datasheet: www.ti.com/opa365-ca

Also see:

- [What does 'rail to rail' input operation really mean?](#)
- [Baker's Best](#)