Do You Really Need Rail-to-Rail Input Amplifiers?

ABSTRACT

Many engineers gravitate toward RRI amplifiers without considering their actual circuit requirements or additional BOM cost. This application report describes when RRI amplifiers are required and when they are not. Specific circuits discussed include a buffer circuit, a non-inverting circuit, an inverting circuit, a transimpedance amplifier circuit, and a low-side current sensing circuit. Crossover distortion concerns are also discussed for each circuit.

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1 Introduction

A rail-to-rail input (RRI) amplifier is defined by its input common-mode voltage range, which includes both the positive and negative supply rails. The input common-mode voltage (V_{CM}) is the most important factor when deciding whether or not an RRI amplifier is required for a given circuit. Input common-mode voltage is the average voltage applied to the inputs of the amplifier, calculated in Equation 1.

$$V_{CM} = \frac{V_{IN+} + V_{IN-}}{2} \quad (1)$$

Where

- V_{IN+} is the voltage applied to the amplifier's non-inverting input
- V_{IN-} is the voltage applied to the amplifier's inverting input
- V_{CM} is the input common mode voltage

Depending on the topology of the amplifier circuit, the V_{CM} can change with the input signal or stay constant. The input common-mode voltage range is the range of allowable input common-mode voltages that will produce linear output behavior and is always specified in the datasheet in relation to the amplifier's supply rails. For example, the input common-mode voltage range of the OPA375 is shown in Table 1. The input common-mode voltage range extends to V_-, the negative rail, but only extends to 1.2 V below V_s, the positive rail, meaning this is not an RRI amplifier. For more details about the OPA375's input voltage range, output swing, or test conditions, please see the OPA375 datasheet.

Table 1. OPA375 Input Voltage Range

Parameter	Min	Max	Unit
V_{CM} (common-mode voltage range)	(V-)	(V_s) - 1.2	V

Table 2. OPA375 Output Swing

Parameter	Typ	Max	Unit
V_o (voltage output swing from supply rails)	8	10	mV

Table 2 shows the output swing of the OPA375. The OPA375 can swing within 10 mV of both the positive and negative rails, so it is a rail-to-rail output amplifier. Although input limitations are the focus of this application report, it is also important to consider output limitations as a possible source of clipping in the following test circuits.

Equation 2 is this application report's fundamental inequality, which describes the input common-mode voltage range for a given amplifier. This inequality can be derived for a specific amplifier using the information found in the input voltage range section of its datasheet.

$$V_- \le V_{CM} \le V_s - V_{CM\_LIM} \quad (2)$$

Where

- V_{CM} is the input common mode voltage
- V_s is the positive supply voltage
- V_- is the negative supply voltage
- V_{CM_LIM} is the input common-mode limit from the datasheet, equal to 1.2 V for the OPA375

Equation 2 forms the starting point of all input common-mode voltage analysis in all of the following test circuits, which use OPA375.

One final concept is important to keep in mind when selecting an amplifier circuit topology and choosing between an RRI or non-RRI amplifier. In order to allow the common-mode input voltage to swing to both rails, RRI amplifiers use two pairs of input transistors. One pair of input transistors (often N-FETs) allows input common-mode voltages to swing slightly above the positive rail and the other pair of input transistors (often P-FETs) allows input common-mode voltages to swing slightly below the negative rail.

Unfortunately, the two pairs of input transistors have completely uncorrelated input offset voltages, and when the amplifier switches between input pairs, the input offset voltage suddenly changes, which causes the output voltage to distort. This distortion, called crossover distortion, can be large or small depending on the amplifier and the circuit topology. Some circuit topologies keep the input common-mode voltage constant, so they are immune to crossover distortion. Note that non-RRI input amplifiers will never have crossover distortion. The crossover region, which is the input common-mode voltage where the amplifier switches between input transistor pairs, is typically between 1-2 V from the positive supply rail. For example, the TLV9062 is an RRI amplifier very similar to the OPA375, and its crossover region occurs approximately 1.4 V from the positive supply rail. As long as the input common-mode voltage is kept away from the crossover region, crossover distortion will not occur. A more detailed explanation of crossover distortion can be found in the TI Precision Labs videos. In addition to analyzing whether or not RRI amplifiers are needed in various circuit topologies, the following examples also discuss whether or not crossover distortion could be an issue.

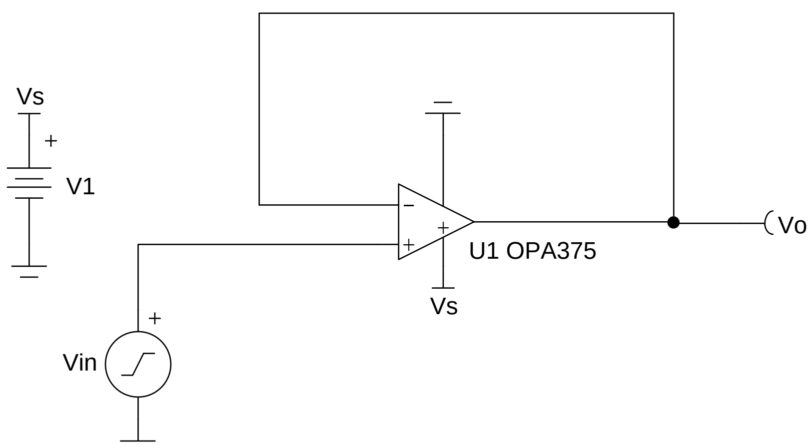
2 Buffer Amplifier Circuit

A buffer circuit is a simple voltage follower where the output voltage equals the input voltage. Because the input signal feeds directly into the non-inverting input, the input common-mode voltage is equal to the input signal. This means that crossover distortion is a concern if RRI amplifiers are needed. This section will discuss buffer circuits with AC input signals and DC input signals. More detailed analysis of the buffer amplifier circuit is available in the *Analog Engineer's Circuit Cookbook: Amplifiers*.

2.1 AC Input Signals

Because the buffer circuit's input common mode voltage is equal to the input signal, the peak voltage of the input signal must not violate Equation 2. Both examples in this section use the circuit shown in Figure 1, and in both examples the positive rail is 5 V and the negative rail is 0 V.

Figure 1. Buffer circuit schematic for examples with AC input signals

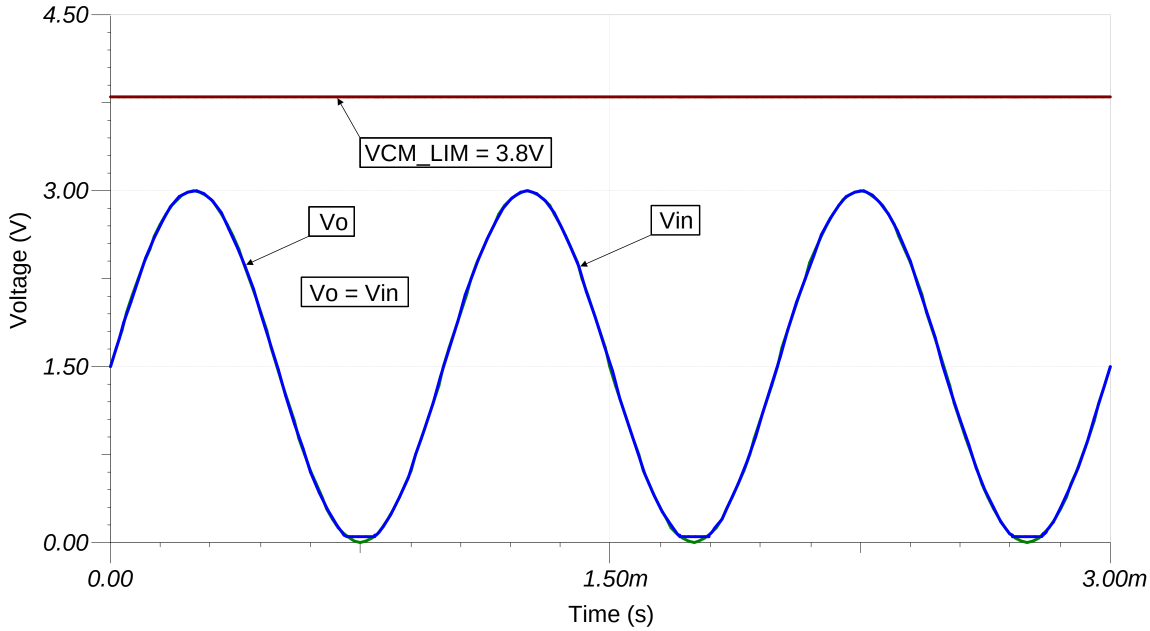


Solving Equation 2 for the OPA375 using V_s = 5 V yields Equation 3. This inequality must be true in order to avoid clipping or other non-linear behavior.

$$
\begin{aligned}
V_- \le V_{in} &\le V_s - V_{INCM\_LIM} \\
0V \le V_{in} &\le 5V - 1.2V \\
0V \le V_{in} &\le 3.8V
\end{aligned}
\quad (3)
$$

In the first example, the AC input signal (V_{in}) is 3 V_{pp} with a DC offset of 1.5 V. This makes the peak input voltage 3 V. This satisfies Equation 3, so the output voltage should not clip, which the simulation in Figure 2 demonstrates.

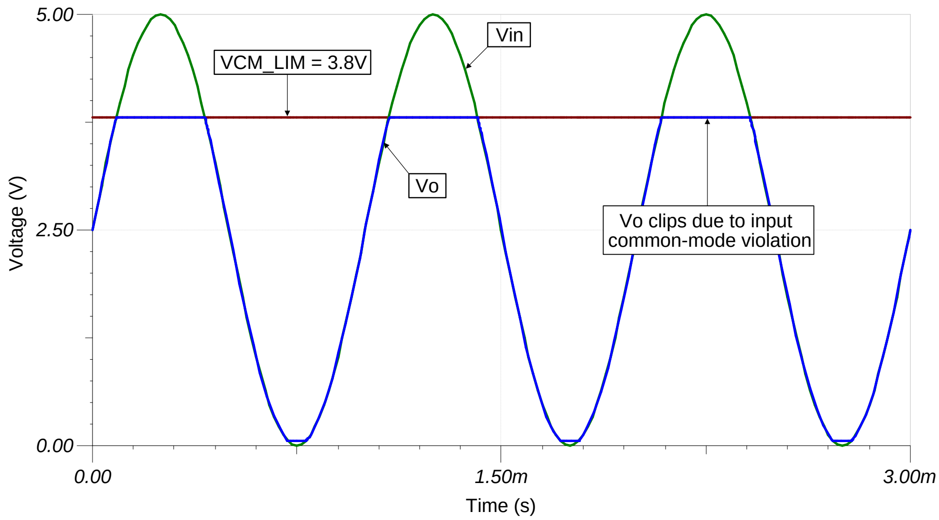
Figure 2. Transient simulation for AC buffer circuit example 1



Note that the output voltage clips close to 0 V; this is due to the output voltage swing limitation, not the input common-mode range. In this case, a non-RRI amplifier can be used because the input common-mode voltage range will never be violated. A rail-to-rail amplifier could also be used, but it would provide no additional benefits. Depending on the amplifier, an RRI amplifier could induce crossover distortion if the input voltage rose high enough that the amplifier switched between input transistor pairs.

In the second example, the AC input signal (V_i) is 5 V_{pp} with a DC offset of 2.5 V. This makes the peak input voltage 5 V. This does not satisfy Equation 3, so the output signal should show nonlinear behavior. The transient simulation shown in Figure 3 demonstrates output clipping at 3.8 V. Note that the output could also swing to the positive rail instead of clipping at 3.8 V. In this case an RRI amplifier is needed to avoid nonlinear output behavior.

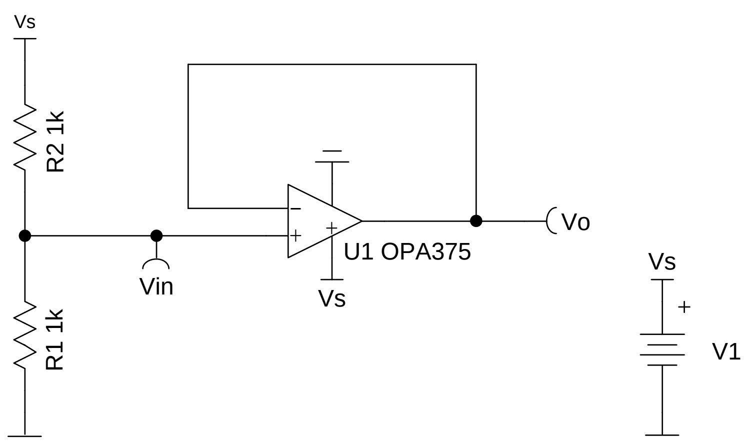
Figure 3. Transient simulation for AC buffer circuit example 2



2.2 DC Input Signals

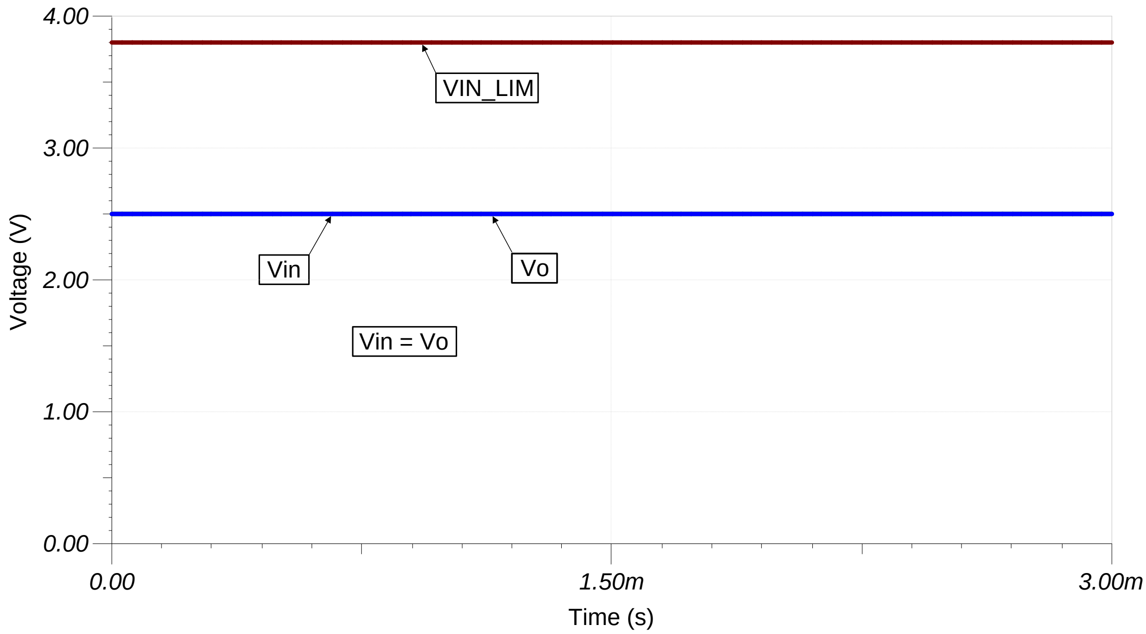
When a DC input signal is applied to the buffer amplifier circuit, the DC voltage must not violate Equation 2. The following two examples use the circuit in Figure 4 . The resistor divider between the positive supply and ground sets the DC input voltage and therefore the input common-mode voltage. The supply voltage is different in each example. For constant DC inputs, crossover distortion is not a concern because the input common-mode voltage is not changing.

Figure 4. Buffer circuit schematic for DC input signals



In the first example, the positive supply voltage is 5 V, which sets the DC input voltage (V_{in}) to 2.5 V. Solving Equation 2 for the OPA375 with a 5-V positive supply once again yields Equation 3. The 2.5-V DC input satisfies this inequality, so the output will not clip. Figure 5 shows the transient simulation that supports this conclusion. Notice that V_{in} exactly matches V_o, both of which are 2.5-V DC. In this case, non-RRI amplifiers will work as well as RRI amplifiers.

Figure 5. Transient simulation for DC buffer circuit example 1

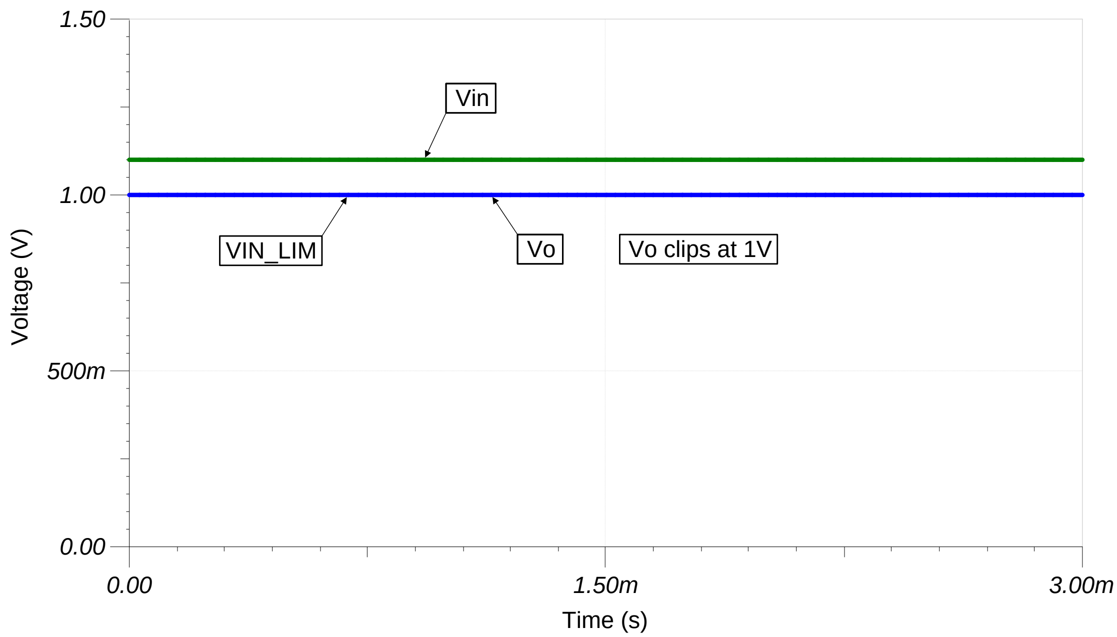


In the second example, the positive supply voltage is 2.2 V, which sets V_{in} to 1.1 V. Evaluating Equation 2 for the OPA375 with a 2.2-V positive supply voltage yields the following inequality:

$$V_{-} \leq V_{in} \leq V_s - V_{INCM\_LIM}$$
$$0V \leq V_{in} \leq 2.2V - 1.2V$$
$$0V \leq V_{in} \leq 1V \quad (4)$$

This time, V_{in} does not satisfy Equation 4 because it is greater than 1 V. When V_{in} is greater than 1 V, the output will behave nonlinearly. In this case the nonlinear behavior is output clipping. Figure 6 is the transient simulation for this example, which shows V_{in} at 1.1 V and V_o clipping at 1 V. Note that in this example the output clips at 1 V, which is the maximum value in the linear rage for the input common mode voltage. This is not always the case, and the linear input common mode voltage range should only be used to determine if the output voltage will behave linearly, and it should not be used to attempt to determine the output behavior if the linear range is violated. In order to avoid nonlinear output behavior, this example requires an RRI amplifier.

Figure 6. Transient simulation for DC buffer circuit example 2



When designing a buffer circuit, RRI amplifiers are not required as long as the following equation is satisfied.

$$V_{in} \leq V_s - V_{INCM\_LIM} \quad (5)$$

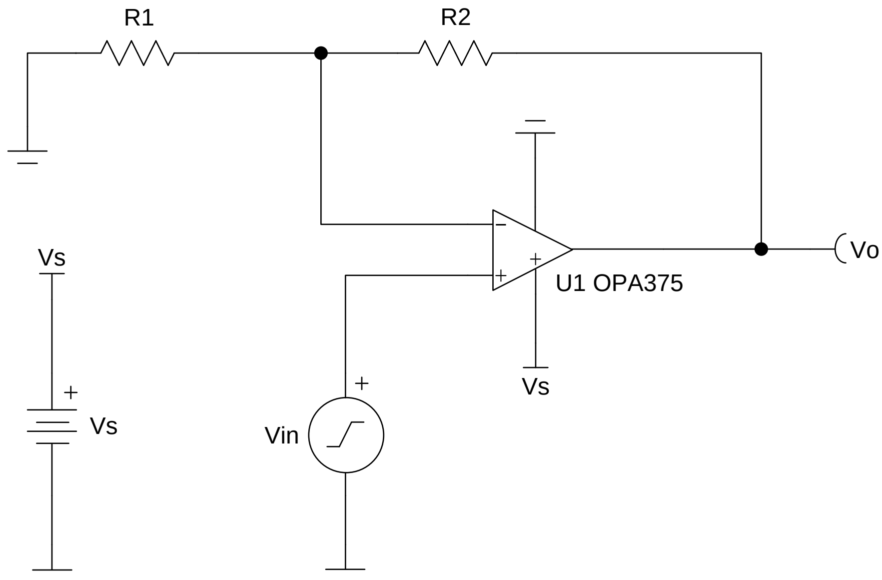
Where

- V_{in} is the maximum voltage of the input signal
- V_s is the positive supply voltage
- V_{INCM_LIM} is the input common-mode limit from the amplifier datasheet

3 Non-Inverting Amplifier Circuit

A non-inverting amplifier circuit amplifies the input signal with a signal gain set by its resistors. Figure 7 shows the non-inverting amplifier circuit that will be analyzed in this section. Because the input signal is applied directly to the non-inverting input node of the amplifier, the amplifier's input common-mode voltage is equal to the input signal. Like the buffer circuit, the non-inverting amplifier circuit's input common mode voltage is limited by Equation 2.

Figure 7. Non-inverting amplifier circuit schematic



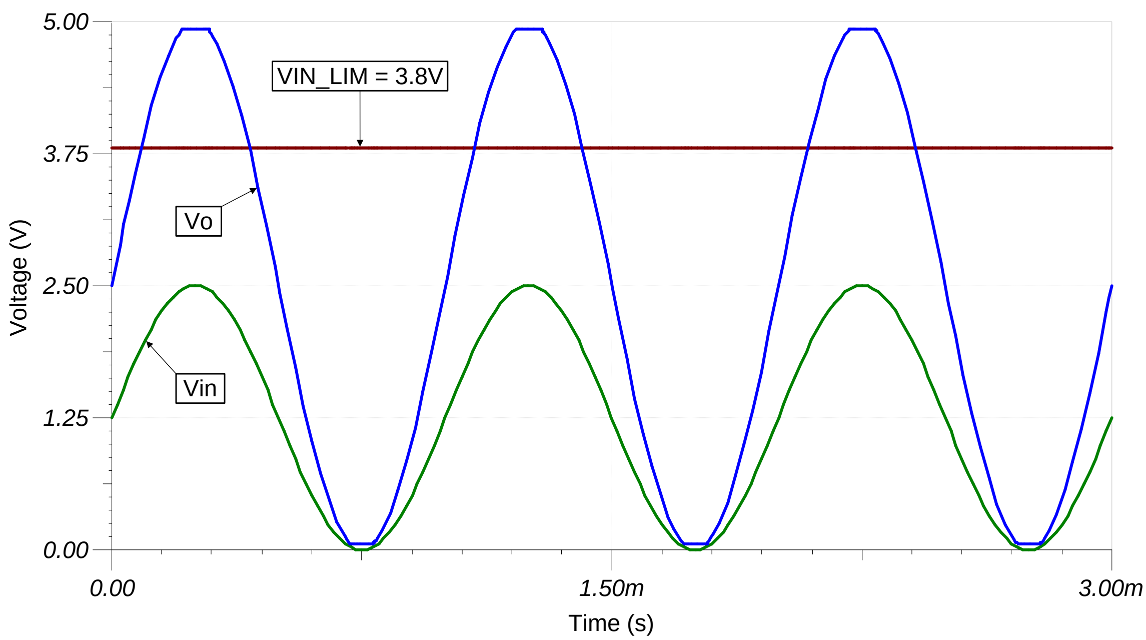
The formula to calculate the circuit's signal gain is shown in Equation 6.

$$G = \frac{R2}{R1} + 1 \quad (6)$$

As long as Equation 2 is satisfied, non-RRI amplifiers will perform just as well as rail-to-rail amplifiers for this application. Often, when the signal gain is greater than 1, RRI amplifiers are not required. This is not always true with low supply voltages, so this should be double-checked. If an RRI amplifier is used with a low-gain configuration, this topology can be sensitive to crossover distortion. High-gain configurations will likely not be sensitive to crossover distortion because the input common-mode voltage should stay very low and away from the crossover region. The following three examples examine some situations in which RRI amplifiers are needed and some in which they are not needed. Additional analysis of the non-inverting amplifier circuit can be found in the *Analog Engineer's Circuit Cookbook: Amplifiers*.

In the first example, R2 = 1 kΩ, R1 = 1 kΩ, the positive supply (V_S) is 5 V, and the AC input voltage (V_{in}) is 2.5 V_{pp} with a DC offset of 1.25 V. Solving Equation 6 yields a gain of 2. The input common-mode limitations from Equation 2 simplify to Equation 3. The maximum input common-mode voltage is equal to the maximum input voltage, which is 2.5 V. This satisfies Equation 3, so the output should not display any nonlinear behavior due to input common-mode range violations. Both the AC input signal and its DC offset will see the circuit's gain. With a gain of 2, the expected output is a 5-V_{pp} AC signal with a DC offset of 2.5 V. Figure 8 shows the transient simulation of this circuit.

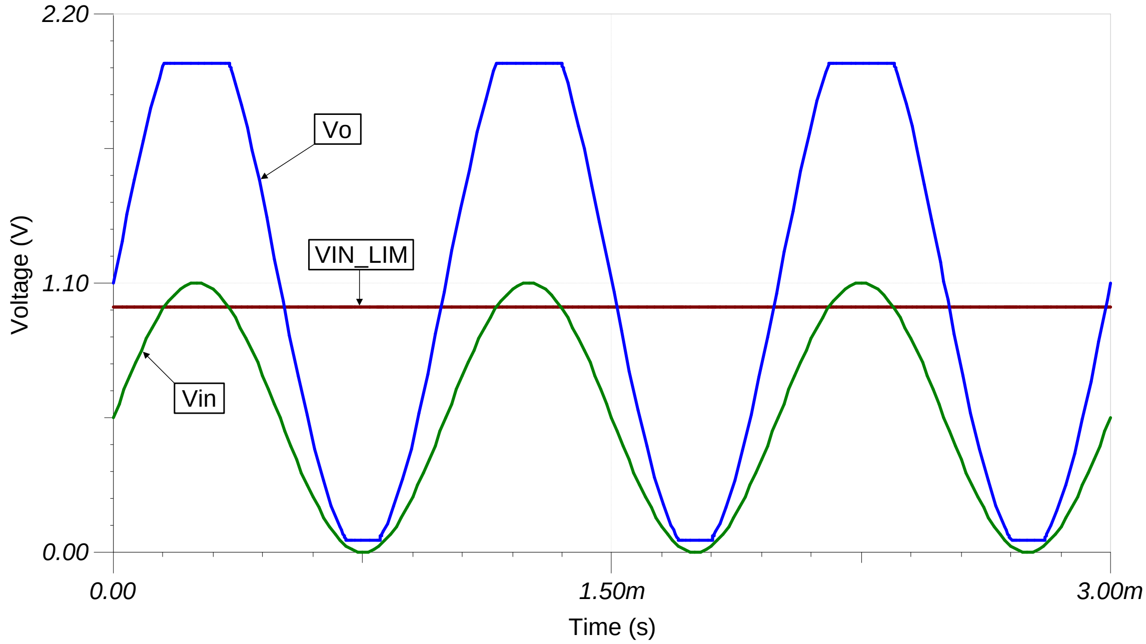
Figure 8. Transient simulation for non-inverting amplifier circuit example 1



Notice that V_{in} is well below the upper limit of the input common-mode voltage range. However, some clipping can still be seen in V_o, which does not quite reach 5 V. This is due to the output swing limitations of the amplifier, not a violation of the input common-mode voltage range. Though a circuit designer may wish to reduce the gain to avoid output swing limitations, he or she does not need to worry about violating the input common-mode voltage range in this case. A non-RRI amplifier would work well for this application, and an RRI amplifier would not provide any additional benefit.

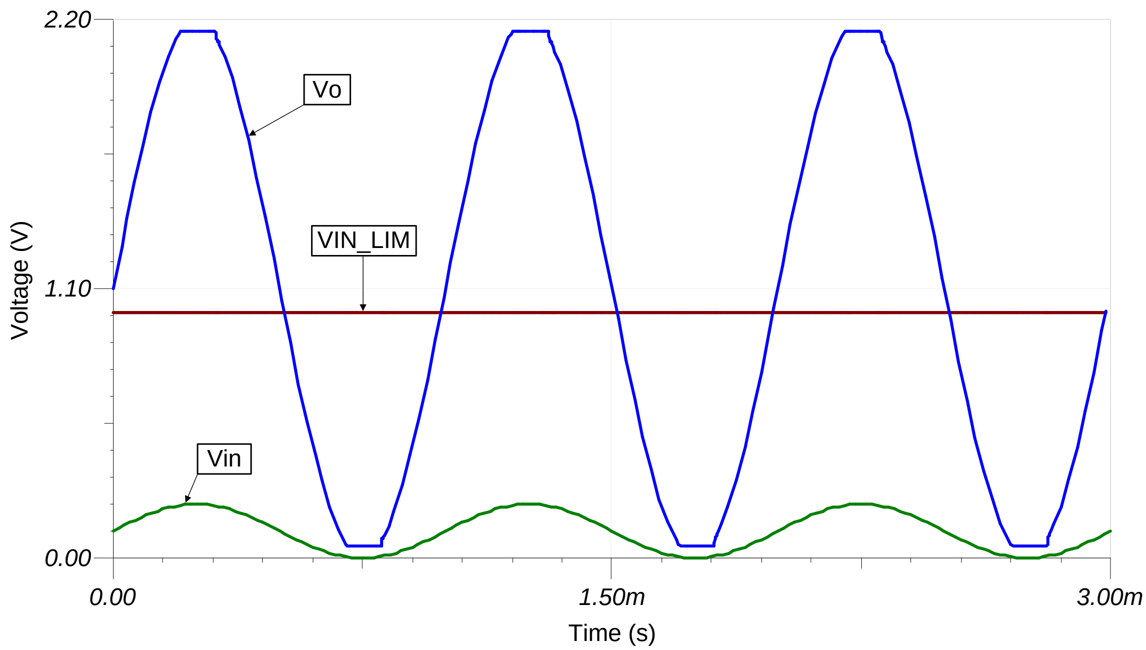
In the second example, R2 = 1 kΩ, R1 = 1 kΩ, the positive supply (V_S) is 2.2 V, and the AC input voltage (V_{in}) is 1.1 V_{pp} with a DC offset of 0.55 V. Once again, solving Equation 6 yields a gain of 2. Using the supply voltage to solve for the input common-mode voltage limitations yields Equation 4. The maximum input common-mode voltage is 1.1 V, which violates Equation 4. This means that the output will display nonlinear behavior. With a gain of 2, the expected output is 2.2-V_{pp} AC with a DC offset of 1.1 V. Figure 9 displays the transient simulation of this circuit. V_o clearly clips at 2.0 V, though it could also be forced to the positive rail. This is caused by the input common-mode range violation, not the output swing limitations of the amplifier. Notice that V_{in} is greater than the upper limit of the input common-mode voltage range when V_o clips. To avoid this nonlinear output behavior, an RRI amplifier is required for this application.

Figure 9. Transient simulation for non-inverting amplifier circuit example 2



In the third and final example for the non-inverting amplifier circuit, R2 = 9 kΩ, R1 = 1 kΩ, the positive supply (V_S) is 2.2 V, and the AC input voltage (V_{in}) is 0.22 V_{pp} with a DC offset of 0.11 V. In this case, solving Equation 6 yields a gain of 10. Because the supply voltages are identical to those in the second example and every example uses the OPA375, Equation 4 also describes the input common-mode voltage limitations for this circuit. The maximum input common-mode voltage is 0.22 V, which satisfies Equation 4. The output should not display any nonlinear behavior due to input common-mode voltage range violations, as shown in Figure 10. V_o still displays some clipping, but this is due to the output swing limitations of the amplifier, not due to input common-mode voltage range violations. For most high-gain circuits, V_{in} is well below the upper limit of the input common-mode range, meaning that a RRI amplifier is often not required.

Figure 10. Transient simulation for non-inverting amplifier circuit example 3



For basic non-inverting amplifier circuits, the following inequality can be used to determine whether or not RRI amplifiers are required. As long as Equation 7 holds true, RRI amplifiers are not required. Equation 7 is a simplification of the previous equations discussed in this section. The positive supply voltage V_s is the absolute maximum output voltage that the amplifier could drive (less output swing limitations), so dividing V_s by the circuit's gain (G) yields the maximum acceptable input voltage. Because the input signal is equivalent to the input common-mode voltage for the non-inverting amplifier circuit, as long as the input signal satisfies the input common-mode limitations on the right sides of the inequality, an RRI amplifier is not required.

$$\frac{V_s}{G} \leq V_s - V_{INCM\_LIM} \tag{7}$$

Where

- V_s is the positive supply voltage
- G is the circuit's gain
- V_{INCM_LIM} is the input common-mode limitation from the amplifier datasheet

For AC coupled non-inverting amplifiers, a slightly different inequality should be used. An AC coupled non-inverting amplifier's input common-mode voltage is the sum of both an AC input signal and a DC reference voltage. Equation 8 includes this DC reference voltage on the left side of the inequality. In this case the reference voltage is assumed to be set to mid-supply, but this term can be replaced with whatever reference voltage the circuit designer selects. The AC coupled non-inverting amplifier circuit will act like a buffer for the DC reference voltage, so this term does not need to be divided by the circuit's gain. As long as Equation 8 is satisfied, an AC coupled non-inverting amplifier circuit does not need an RRI amplifier.

$$\frac{V_s}{2} + \frac{V_s}{G} \leq V_s - V_{INCM\_LIM} \tag{8}$$

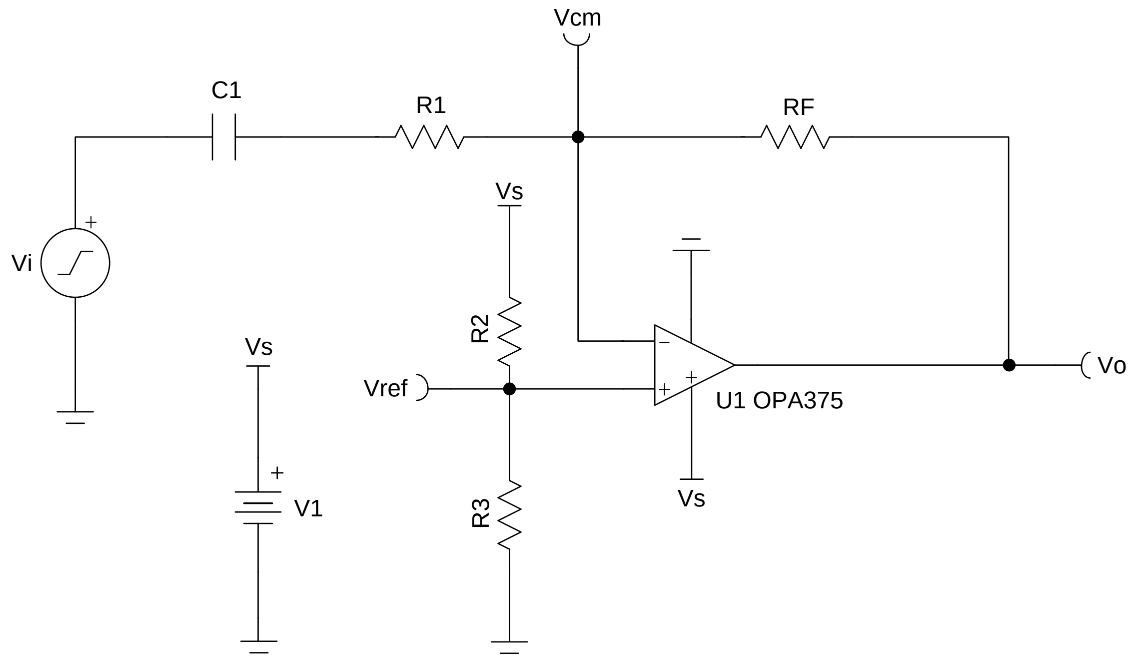
Where

- V_s is the positive supply voltage
- G is the circuit's gain
- V_{INCM_LIM} is the input common-mode limitation from the amplifier datasheet

4 Inverting Amplifier Circuit

An inverting amplifier circuit inverts the input signal with a signal gain set by its resistors. Figure 11 shows a common example of an inverting amplifier circuit. In this case, the input common-mode voltage is set by V_{ref}, which is determined by the resistor divider between the positive supply (V_s) and ground. Another common practice is to tie the non-inverting input to ground. Using the resistor divider at the non-inverting input allows the circuit designer to set the DC offset at the output. The input signal is AC-coupled to the circuit by capacitor C1, so any DC offset from the input signal is filtered out. For DC inputs, the circuit is essentially a buffer circuit, so V_{ref} is passed directly to the output.

Figure 11. Inverting amplifier circuit schematic



The gain for this circuit can be calculated using the following equation:

$$G_{AC} = -\frac{RF}{R1} \qquad G_{DC} = 0 \tag{9}$$

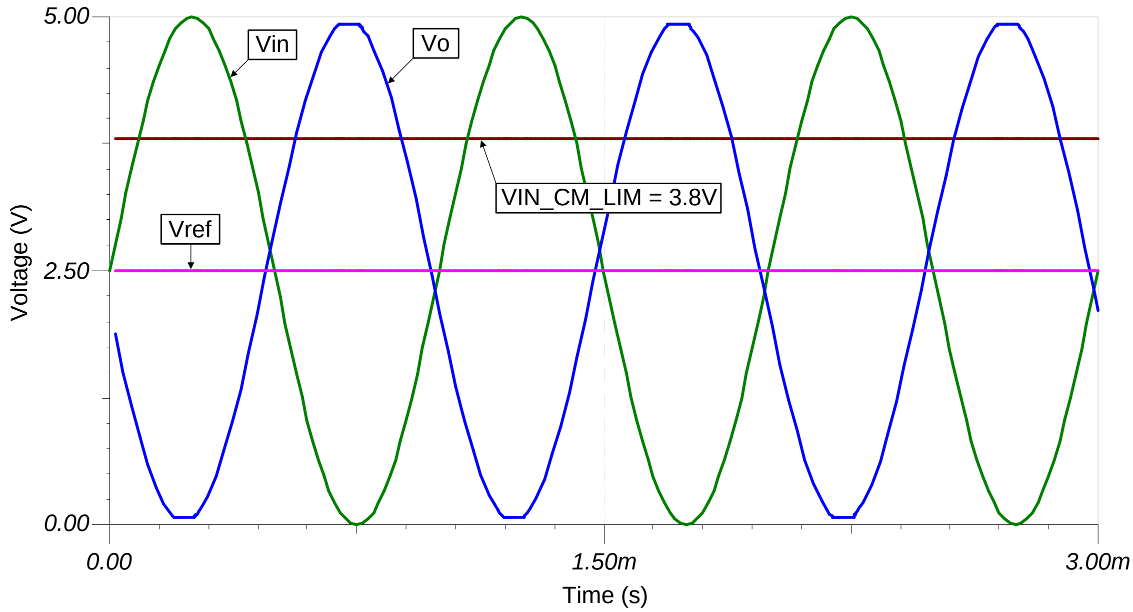
From Equation 9 we can create the transfer function for this circuit:

$$V_o = -\frac{RF}{R1}(V_{in,\ AC}) + V_{ref} \tag{10}$$

Because the input common-mode voltage is set by V_{ref}, inverting amplifiers are not limited by the input common-mode voltage range as long as V_{ref} satisfies Equation 2. If this requirement is met, non-RRI amplifiers will work just as well as RRI amplifiers in this application. Additionally, crossover distortion is not a concern in this circuit topology because the input common-mode voltage is held constant at V_{ref}. The following examples show two inverting amplifier circuits that have V_{ref} set correctly and do not have any input common-mode limitations and one circuit that shows nonlinear output behavior because V_{ref} is set incorrectly. For more information about the inverting amplifier circuit, please see the *Analog Engineer's Circuit Cookbook: Amplifiers*.

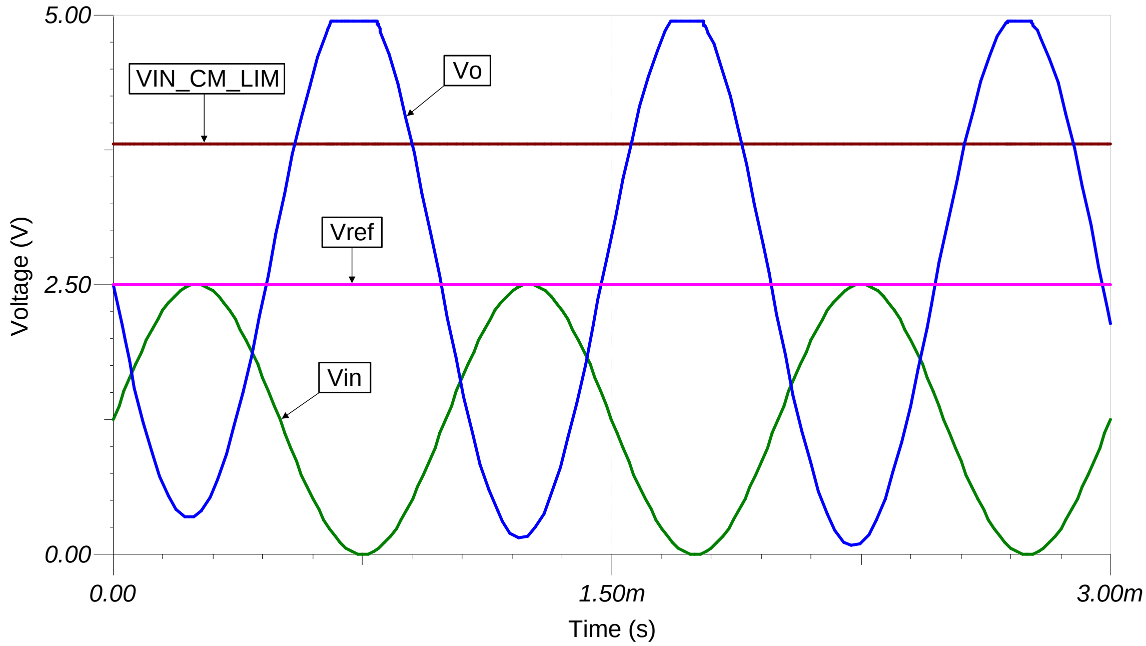
In the first example, RF = 1 kΩ, R1 = 1 kΩ, R2 = R3 = 1 kΩ, the positive supply (V_S) is 5 V, and the AC input voltage (V_{in}) is 5 V_{pp} with a DC offset of 2.5 V. Because V_S = 5 V, Equation 3 once again describes the input common-mode voltage limitations. V_{ref} satisfies these limitations, so this circuit is not limited by the input common-mode voltage. Solving Equation 10 yields an expected output voltage of 5-V_{pp} AC with a DC offset of 2.5 V. Note that the negative gain translates to a phase shift of 180°. The transient simulation shown in Figure 12 almost matches the expected output, but there are some signs of output clipping. The output signal does not quite reach 5 V or 0 V. This is due to output swing limitations, not input common-mode voltage limitations. Note that the input signal can swing to the supply rails without affecting the input common mode voltage. In this case, a non-RRI amplifier will work well.

Figure 12. Transient simulation for inverting amplifier example 1



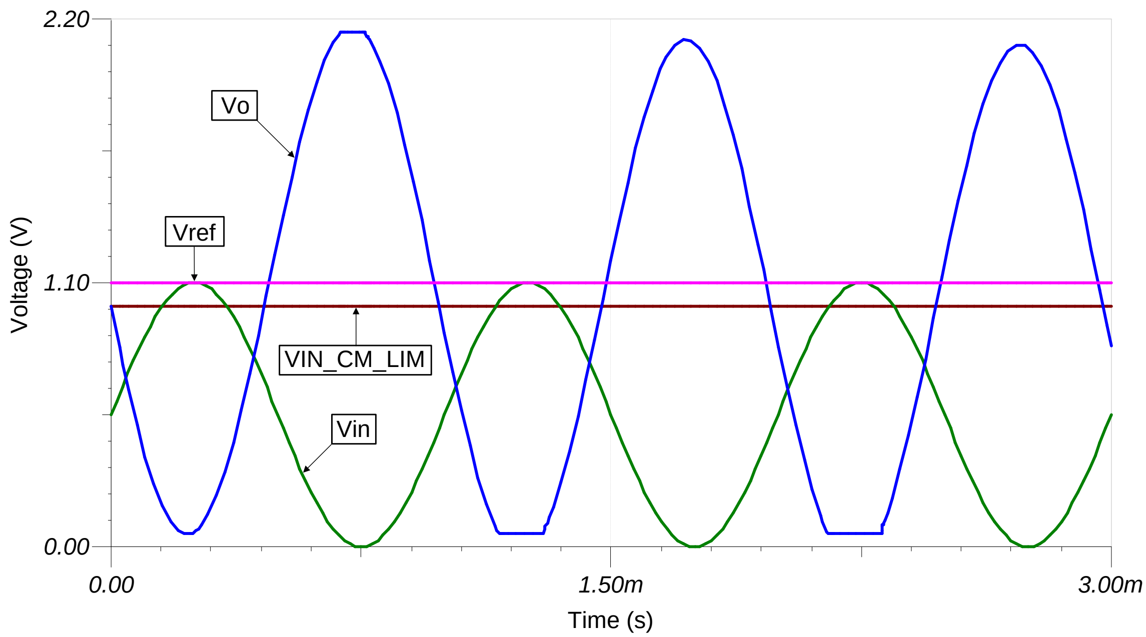
In the second example, RF = 2 kΩ, R1 = 1 kΩ, R2 = R3 = 1 kΩ, the positive supply (V_s) is 5 V, and the AC input voltage (V_{in}) is 2.5 V_{pp} with a DC offset of 2.5 V. The major differences between this example and the previous example are the magnitude of the input signal and the gain. The supply voltages have not changed, so Equation 3 still describes the input common-mode voltage limitations. V_{ref} has also not changed, so it still satisfies Equation 3 and there should be no nonlinear output behavior due to input common-mode voltage range violations. Solving Equation 10 yields an expected output voltage of 5-V_{pp} AC with a DC offset of 2.5 V. The phase of the output signal should be shifted by 180° compared to the input signal. Figure 13 shows the transient simulation for this circuit, which mostly matches the calculated output. Like the previous example, this transient simulation shows some output clipping due to output swing limitations, not input common-mode range violations. A non-RRI amplifier will work just as well as an RRI amplifier in this case.

Figure 13. Transient simulation for inverting amplifier example 2



In the final example for the inverting amplifier circuit, RF = 2 kΩ, R1 = 1 kΩ, R2 = R3 = 1 kΩ, the positive supply (V_S) is 2.2 V, and the AC input voltage (V_{in}) is 1.1 V_{pp} with a DC offset of 0.55 V. This example has a different supply voltage than the previous two examples, so Equation 2 must be reevaluated. The input common-mode range has already been derived for circuits with a 2.2-V positive supply, so this circuit will also use Equation 4. V_{ref} is set to mid-supply, which is 1.1 V in this case. This does not satisfy Equation 4, so the output will display some nonlinear behavior. Solving Equation 10 yields an expected output voltage of 2.2-V_{pp} AC with a DC offset of 1.1 V. The phase of the output signal should be shifted by 180° compared to the input signal. The transient simulation in Figure 14 shows some clipping of the output signal. As the output approaches the positive rail, the output clips due to output swing limitations. The output clips more severely near ground, and this is due to input common-mode range violations. Because V_{ref} violates the input common-mode range, an RRI amplifier is required for this application.

Figure 14. Transient simulation for inverting amplifier example 3



As long as Equation 11 is satisfied, RRI amplifiers are not needed for basic inverting amplifier circuits. This inequality is a simplified version of the equations used previously in this section and assumes that V_{ref} (the voltage at the positive input) is set to mid-rail. For inverting amplifiers with the positive input tied to ground, RRI amplifiers are never needed. Both the previous statement and Equation 11 also apply to AC coupled inverting amplifiers.

$$\frac{V_s}{2} \leq V_s - V_{INCM\_LIM} \tag{11}$$

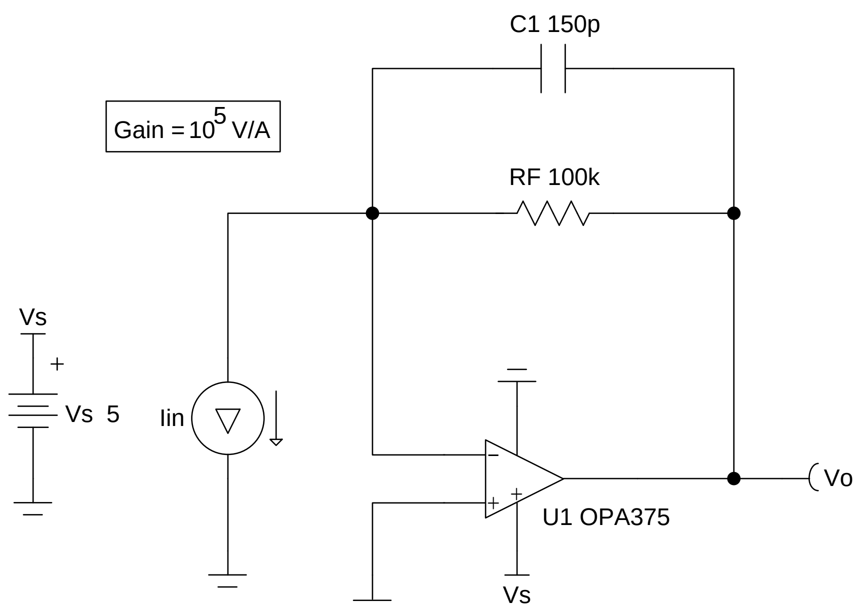
Where

- V_s is the positive supply rail
- V_{INCM_LIM} is the input common-mode limitation from the amplifier datasheet

5 Transimpedance Amplifier Circuit

The transimpedance amplifier circuit converts an input current source into an output voltage. The gain (in units of V/A) is controlled by the feedback resistor. Figure 15 shows a common implementation of a transimpedance amplifier circuit. This is a simplified circuit to gain general understanding of transimpedance amplifiers, and a real-world circuit using a photodiode is discussed later in this section. Like the inverting amplifier circuit, the input common-mode voltage is set by the DC voltage at the non-inverting input. This input is often connected to ground or a small offset voltage, which would bias the output slightly above ground. This makes non-RRI amplifiers a good fit for almost all transimpedance amplifier applications. If an RRI amplifier were used, crossover distortion would not be a concern because the input common-mode voltage is constant. More detailed analysis of the transimpedance amplifier circuit can be found in the *Analog Engineer's Circuit Cookbook: Amplifiers*.

Figure 15. Transimpedance amplifier circuit schematic



For the circuit in Figure 15, the gain can be calculated using the following equation:

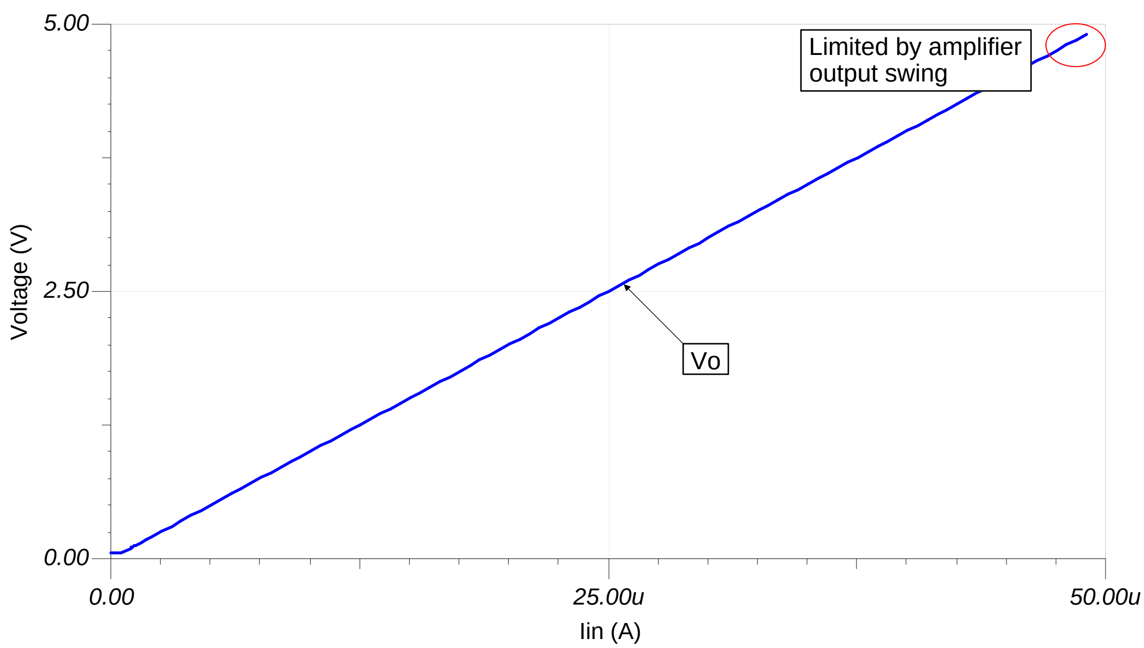
$$G = \frac{V_o}{I_i} = R_f \quad (12)$$

Where

- G is the gain in V/A
- V_o is the output voltage
- I_i is the input current flowing from the output through the feedback resistor
- R_f is the feedback resistor

In this example, the positive supply voltage (V_s) is 5 V, the feedback resistor R1 = 100 kΩ, and the input current (I_{in}) linearly ramps from 0.5 µA to 50 µA. This example once again uses a 5-V positive supply, so Equation 3 describes the input common-mode voltage range. With the non-inverting input tied to ground, the input common-mode voltage is 0 V, which satisfies Equation 3. From Equation 12, the output voltage is simply the input current multiplied by the feedback resistor. The expected output voltage will ramp from 50 mV to 5 V. Figure 16 shows the DC transfer characteristic simulation for the basic transimpedance amplifier circuit. The simulation is almost identical to the expected output, except that it does not quite reach 5 V due to output swing limitations. The simulation does not display any nonlinear behavior because there are no input common-mode voltage range violations, so both non-RRI and RRI amplifiers will work for this application.

Figure 16. DC transfer characteristic simulation for basic transimpedance amplifier



5.1 Transimpedance Amplifier: Photodiode Model

The previous example of a transimpedance amplifier circuit uses an ideal current source, which is not realistic. A common real-world application of the transimpedance amplifier circuit uses a photodiode in place of the ideal current source. Figure 17 shows a transimpedance amplifier circuit with a photodiode model. For additional analysis of transimpedance amplifiers with photodiodes, see the *Analog Engineer's Circuit Cookbook: Amplifiers*.

Figure 17. Transimpedance amplifier circuit schematic with photodiode model

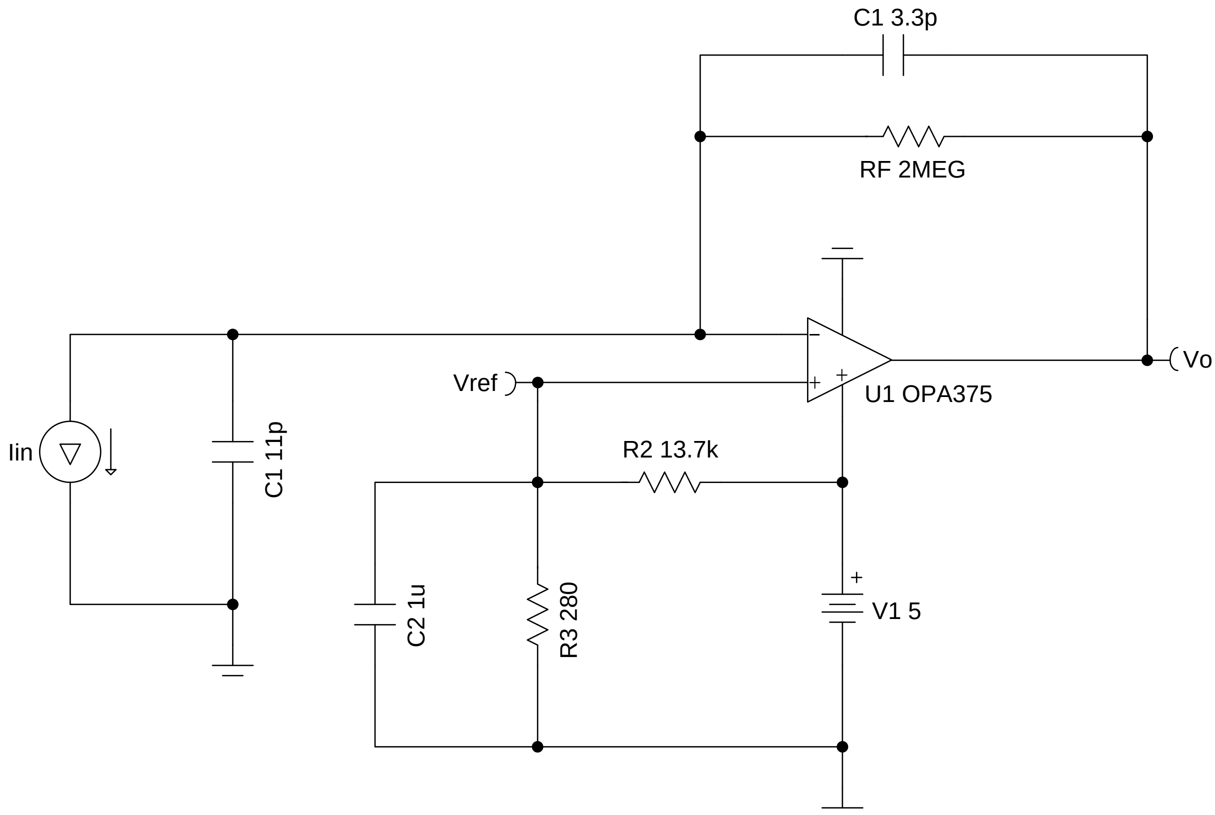
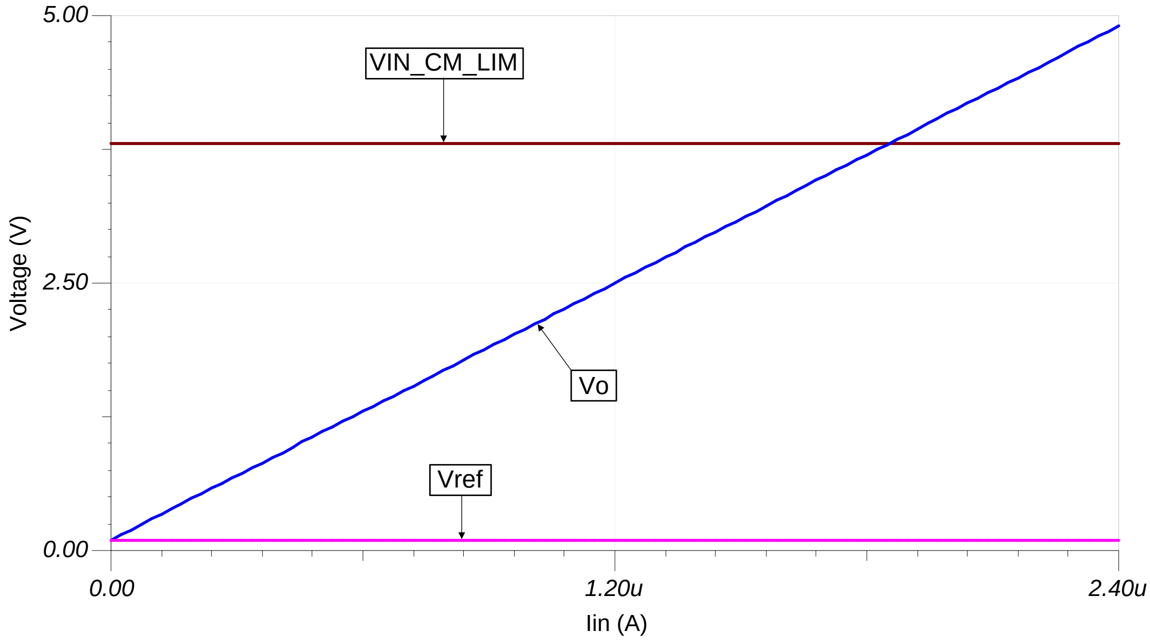


Figure 17 uses the same amplifier and positive supply voltage as the previous transimpedance amplifier example, so Equation 3 still describes its input common-mode voltage range. The voltage at the non-inverting amplifier input is set by the resistor divider, which evaluates to 100 mV. This means that the input common-mode voltage is 100 mV, which satisfies Equation 3, so the output should not show any nonlinear behavior due to input common-mode voltage range violations. The feedback resistor is 2 MΩ, so the output voltage is equal to the input current multiplied by 2×10^6 V/A. With an input current linearly ramping from 0 A to 2.4 µA, the expected output voltage linearly ramps from 0 V to 4.8 V. The DC simulation in Figure 18 shows that the output voltage perfectly matches the predicted output. The simulation confirms that there are no input common-mode voltage range violations. Both non-RRI and RRI amplifiers will work for this application. Either type of amplifier can be used in almost all transimpedance amplifier applications.

Figure 18. DC transfer characteristic simulation for transimpedance amplifier with photodiode model



The input common-mode voltage for a transimpedance amplifier is set by V_{ref}, the voltage at the positive input. This voltage is almost always either connected to ground or set to a very small offset voltage, so RRI amplifiers are almost never required. This concept is summarized in Equation 13.

$$V_{ref} \leq V_s - V_{INCM\_LIM} \tag{13}$$

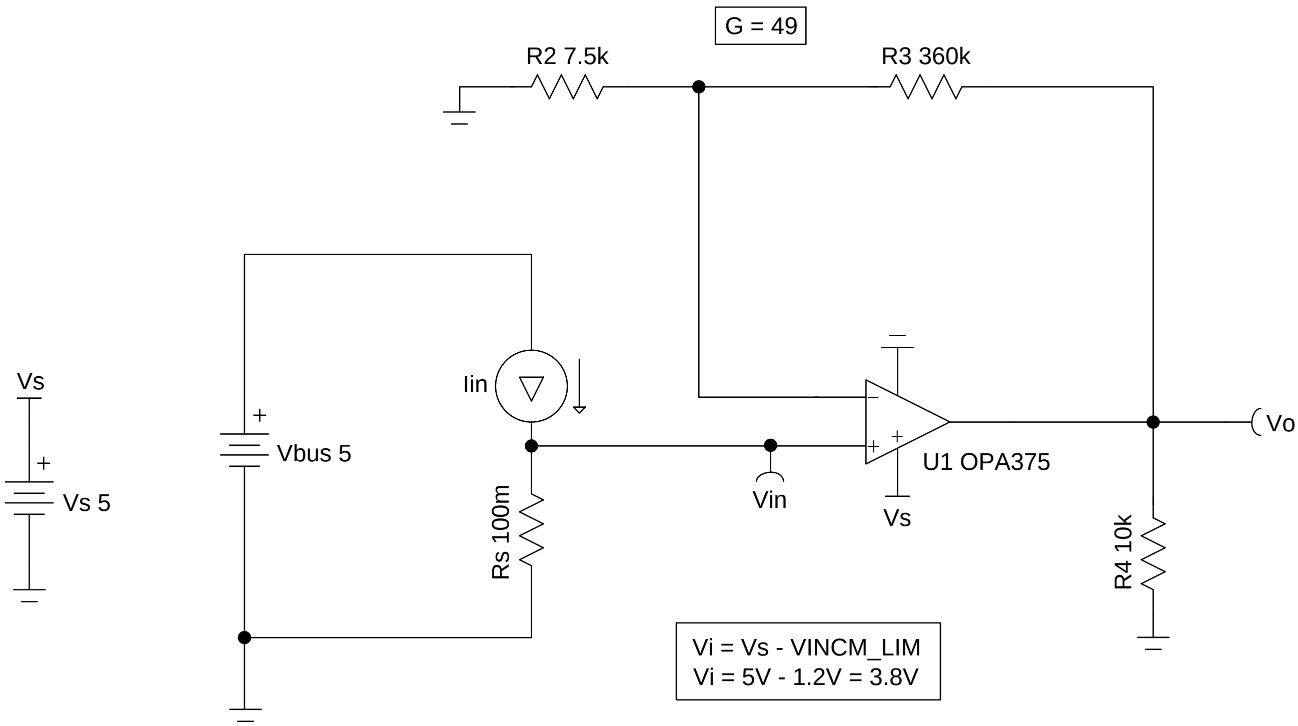
Where

- V_{ref} is the DC reference voltage at the positive input
- V_s is the positive supply voltage
- V_{INCM_LIM} is the input common-mode limitation in the amplifier datasheet

6 Low-Side Current Sensing Circuit

Similar to the transimpedance amplifier, the low-side current sensing circuit detects load currents in a certain range and converts them to a voltage output. A common implementation of a low-side current sensing circuit is shown in Figure 19. Unlike the transimpedance amplifier, the input current to the low-side current sensing circuit is converted to a voltage at the input side of the amplifier, which is then amplified. The input common-mode voltage is set by the non-inverting amplifier input, which is always within a few hundred millivolts above ground. Because this is a high-gain circuit and the input common-mode voltages tend to be very small, non-RRI amplifiers often work well in this application. If an RRI amplifier were used, crossover distortion would not be a concern because the input common-mode voltage swing is so small and so close to the negative rail. Further analysis of both low-side and high-side current sensing circuits can be found in the *Analog Engineer's Circuit Cookbook: Amplifiers*.

Figure 19. Low-side current sensing circuit schematic

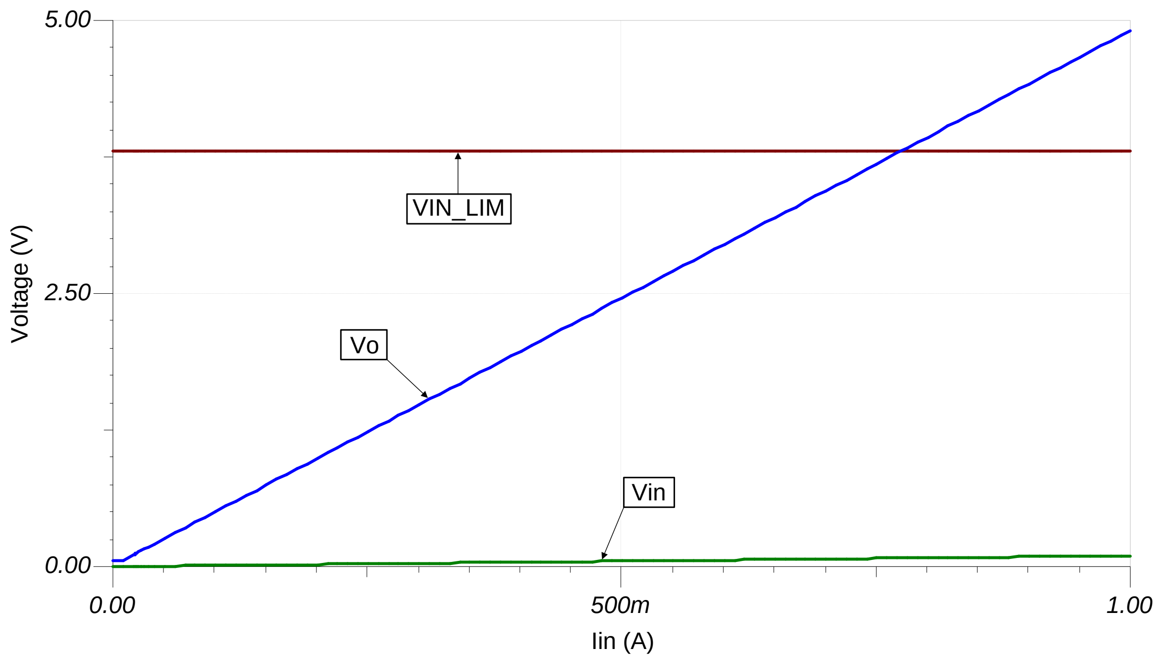


In this example, the gain can be calculated with the following equation:

$$G = \frac{R3}{R2} + 1 = \frac{360k}{7.5k} + 1 = 49 \quad (14)$$

This circuit also uses a 5-V positive supply, so the now-familiar Equation 3 describes the input common-mode voltage range. The input common-mode voltage can be calculated by multiplying the input current by Rs. The input current will ramp linearly from 0 A to 1 A. This yields a minimum input common-mode voltage of 0 V and a maximum input common-mode voltage of 100 mV. Both of these values (and all values between them) satisfy Equation 3, so the output should not show any nonlinear behavior due to input common-mode voltage range violations. The minimum and maximum input common-mode voltages are the same as the minimum and maximum input signal, so using Equation 14 the expected output signal ranges from 0 V to 4.9 V. Figure 20 shows the DC simulation for this circuit, which does not display any nonlinear behavior. The simulated output perfectly matches the calculated output. Because the input common-mode voltage is so small, non-rail-to-rail amplifiers would work well for this application.

Figure 20. DC transfer characteristic simulation for low-side current sensing circuit



Like the transimpedance amplifier, an RRI amplifier is almost never required for a low-side current sensing circuit. This is due to the very low input voltage, which is equivalent to the input common-mode voltage. As long as is satisfied, RRI amplifiers are not needed.

$$V_{in} \le V_s - V_{INCM\_LIM} \quad (15)$$

Where

- V_{in} is the maximum voltage of the input signal
- V_s is the positive supply voltage
- V_{INCM_LIM} is the input common-mode limitation from the amplifier datasheet

7 Conclusion

Non-RRI amplifiers work just as well as RRI amplifiers as long as the following condition is met:

$$V_{CM} \leq V_s - V_{INCM\_LIM}$$

Where

- V_{CM} is the input common-mode voltage
- V_s is the supply voltage
- V_{INCM_LIM} is the input common-mode limit voltage from the datasheet

The output can display nonlinear behavior when V_{CM} exceeds the limit set by the supply and input common-mode limit voltage. If the non-inverting input of the amplifier is either ground or a constant DC voltage within the input common-mode range, the circuit is not limited by input common-mode voltage. In this case, non-RRI amplifiers are a good fit. In circuits with high gains, the input common-mode voltage is usually within the acceptable range, so non-RRI amplifiers are a good fit for these applications as well. In general, it is important to analyze the input common-mode voltage requirements of amplifier circuits before selecting an appropriate amplifier, especially for engineers trying to minimize BOM costs.

Finally, the following table summarizes when RRI amplifiers are not required for each circuit topology discussed in this application report. More detailed explanations of each equation can be found at the end of the related circuit's section, but as long as each equation holds true RRI amplifiers are not needed and will provide no additional benefits to the circuit.

Topology	Equation	Common Applications
Buffer	$V_{in} \leq V_s - V_{INCM\_LIM}$	ADC buffer, Vref buffer
Non-Inverting	$\frac{V_s}{G} \leq V_s - V_{INCM\_LIM}$	Low-side current sensing, non-inverting single-supply
AC Coupled Non-Inverting	$\frac{V_s}{2} + \frac{V_s}{G} \leq V_s - V_{INCM\_LIM}$	Microphone
Inverting	$\frac{V_s}{2} \leq V_s - V_{INCM\_LIM}$	Oscillators
AC Coupled Inverting	$\frac{V_s}{2} \leq V_s - V_{INCM\_LIM}$	Audio signal chain, AC signal gain stage
Transimpedance	$V_{ref} \leq V_s - V_{INCM\_LIM}$	Photodiode, I-V converter
Low-Side Current Sensing	$V_{in} \leq V_s - V_{INCM\_LIM}$	Low-side current sensing

8 References

- *Analog Engineer's Circuit Cookbook: Amplifiers* SLYY137
- TI Precision Labs: Op Amps
- *Op amps with complementary-pair input stages: What are the design trade-offs?* SLYT759

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