# Using fully differential op amps as attenuators, Part 2: Single-ended bipolar input signals

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## Introduction

Fully differential operational amplifiers (FDAs) can easily be used to attenuate and level-shift high-voltage input signals to match the input requirements of lower-voltage ADCs. This article is Part 2 of a three-part series. In Part 1 (see Reference 2) we considered a balanced, differential bipolar input signal and proposed an architecture utilizing an FDA to accomplish the task. In Part 2 we will show how to adapt the circuits presented in Part 1 to a high-voltage, single-ended (SE) bipolar input. Part 3, which will appear in a future issue of the *Analog Applications Journal*, will show the more generic case of an SE unipolar input with arbitrary common-mode voltage. As mentioned in Part 1, the fundamentals of FDA operation are presented in Reference 1, which provides definitions and derivations.

## Attenuator circuit for SE bipolar input

### Using an input attenuator

Now consider a high-amplitude, SE bipolar input signal that needs to be attenuated and level-shifted to the appropriate levels to drive a lower-voltage input ADC. The first step is to modify the differential bipolar input circuit presented in Part 1 to accept an SE bipolar input and keep the amplifier balanced. This is accomplished by grounding one side of the signal source, splitting $R_T$ in half, and grounding the center point. Otherwise the circuit is the same. Splitting $R_T$ in half and grounding the center point are key to keeping the resistances that set the gain on each side of the amplifier balanced so that no offsets are generated. Figure 5 shows the modified circuit.

We can build the circuit as shown (with appropriate values), but we can get the equivalent circuit shown in Figure 6 with a few simple changes: Combine $R_S$, $R_G$, and $R_T/2$ on the alternate input from the signal into an equivalent resistor $R_{G-}$; use reference designator $R_{G+}$ on the positive side; and replace $R_T/2$ with $R_T$. The circuit analysis of Figure 6 is very similar to that of Figure 1 in Part 1 of this series, but the changes in the input configuration result in a new gain equation:

$$\frac{V_{OUT\pm}}{V_{Sig}} = \frac{R_T}{R_S + R_T} \times \frac{R_F}{R_{G+} + R_S \parallel R_T} \quad (4)$$

The noise gain of the FDA can be set to 2 by making the second half of Equation 4 equal to 1:

$$R_{G+} + R_S \parallel R_T = R_F \quad (5)$$

Figure 5. Differential bipolar input circuit modified to accept SE bipolar input

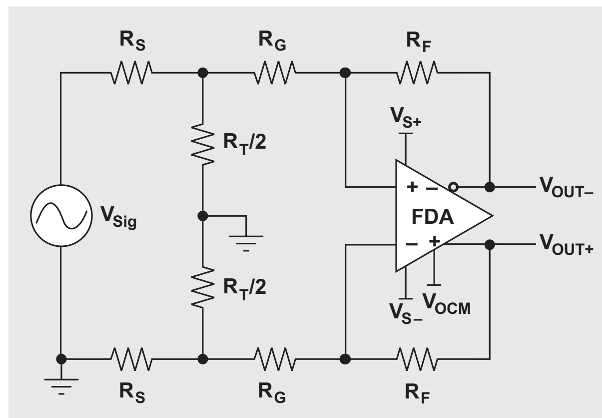
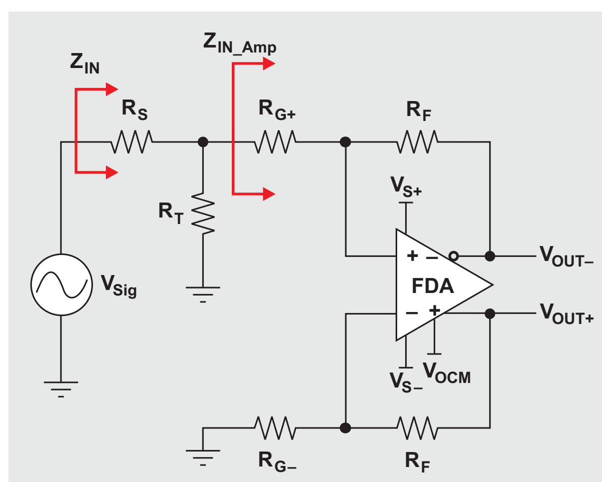



Figure 6. Equivalent SE bipolar input circuit




With this constraint, the overall gain equation reduces to

$$\frac{V_{OUT\pm}}{V_{Sig}} = \frac{R_T}{R_S + R_T}. \quad (6)$$

The design equations provide two degrees of freedom for choosing components. The input impedance is given by

$Z_{IN} = R_S + R_T \parallel Z_{IN\_Amp}$, which is approximated by $Z_{IN} = R_S + R_T \parallel R_{G+}$; so we start by first choosing $R_S$ close to the desired input impedance. We then select $R_F$ in the recommended range for the device and calculate the required value of $R_T$ to give the desired attenuation. These results can be used to calculate $R_{G+}$ and an equivalent value for $R_{G-}$. To see an example Excel® worksheet, go to http://www.ti.com/lit/zip/slyt341 and click Open to view the WinZip® directory online (or click Save to download the WinZip file for offline use). Then open the spreadsheet file FDA_Attenuator_Examples_SE_Bipolar_Input.xls and select the Bipolar SE FDA Input Atten worksheet tab.

#### *Design Examples 3a and 3b*

For Example 3a, let's say that again we have a 20-$V_{PP}$ bipolar (±10-V) input, but this time it is an SE signal. We need a 1-kΩ input impedance and want to use the ADS8321 SAR ADC with a 5-$V_{PP}$ differential input and a 2.5-V common-mode voltage. We choose $R_S$ = 1 kΩ and $R_F$ = 1 kΩ. Rearranging Equation 6 and using substitution, we can calculate

$$R_T = \frac{R_S}{\frac{V_{Sig}}{V_{OUT\pm}} - 1} = \frac{1\ k\Omega}{4-1} = 333.3\ \Omega.$$

The nearest standard 1% value, 332 Ω, should be used. Then, rearranging Equation 5 and using substitution, we can calculate

$$R_{G+} = R_F - R_S \parallel R_T = 1\ k\Omega - 1\ k\Omega \parallel 332\ \Omega = 750\ \Omega,$$

which is a standard 1% value. We can then calculate

$$R_{G-} = R_{G+} + R_S \parallel R_T = 750\ \Omega + 1\ k\Omega \parallel 332\ \Omega = 1\ k\Omega,$$

which is a standard 1% value. These values will provide the needed attenuation and keep the FDA stable. Again the $V_{OCM}$ input on the FDA is used to set the output common-mode voltage to 2.5 V.

The input impedance is $Z_{IN}$ = 1254 Ω, which is higher than desired. If the input impedance really needs to be closer to 1 kΩ, we can iterate with a lower value as before. In this case, using $R_S$ = 787 Ω and $R_F$ = 1 kΩ will yield $Z_{IN}$ = 999 Ω, which comes as close as is possible when standard 1% values are used.

To see a TINA-TI™ simulation of the circuit in Example 3a, go to http://www.ti.com/lit/zip/slyt341 and click Open to view the WinZip directory online (or click Save to download the WinZip file for offline use). If you have the TINA-TI software installed, you can open the file FDA_Attenuator_Examples_SE_Bipolar_Input.TSC to view the example (the top circuit labeled "Example 3a"). To download and install the free TINA-TI software, visit www.ti.com/tina-ti and click the Download button.

The simulation waveforms for Example 3a show that the signal is distorted. Further investigation will show that the input common-mode voltage range of the THS4520 used in the simulation has been violated, causing nonlinear operation. In this case the SPICE model shows a problem; but care must be taken to double-check operation against the data sheet, as not all SPICE models will show this error. For instance, replacing the THS4520 model with the THS4509 will simulate fine, but the actual device has a similar input common-mode voltage range.

One way to correct the problem is to use pull-up resistors from the FDA input pins to the +5-V supply, as described in the THS4520 data sheet. In this case, 2-kΩ pull-up resistors will bring the input common-mode voltage back into linear operation and will have no effect on the gain of the signal. To see a TINA-TI simulation of this corrected circuit (Example 3b), follow the same procedure as for Example 3a, but view the middle circuit labeled "Example 3b." Note that this circuit provides the same results as those shown in Figure 3 of Part 1.

Another way to eliminate the problem with input common-mode voltage is to use the $R_F$ and $R_G$ gain-setting resistors of the FDA as the attenuator, a method that is described next.

#### **Using an FDA's $R_F$ and $R_G$ as an attenuator**

The proposed circuit using gain-setting resistors to obtain an SE bipolar input signal is shown in Figure 7. In this circuit, the FDA is used as an attenuator in a manner similar to using an inverting op amp, as described in Part 1 for the differential bipolar signal. The design equations are the same as in Part 1, except that the input impedance is reduced by approximately half. Thus, the gain (or attenuation) is set by $R_F$ and $R_G$:

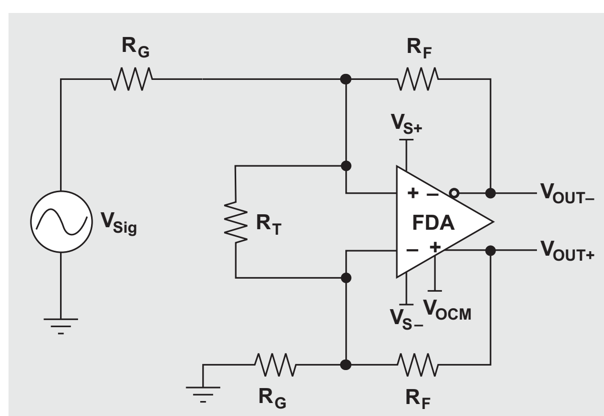
$$\frac{V_{OUT\pm}}{V_{Sig}} = \frac{R_F}{R_G}$$

$R_T$ is used to set the noise gain to 2 for stability; i.e.,

$$R_F = R_G \parallel \frac{R_T}{2},$$

and the input impedance is $Z_{IN} \approx R_G$.

**Figure 7. Using FDA's $R_F$ and $R_G$ as attenuator for SE bipolar input**



***Design Example 4***

Using the same approach as for Example 3a, with $R_F = 1\ k\Omega$, we calculate $R_G = 4\ k\Omega$ (the nearest standard 1% value is 4.02 kΩ) and $R_T = 2.67\ k\Omega$ (the nearest standard 1% value is 2.67 kΩ). This makes $Z_{IN} \approx 4.02\ k\Omega$, and SPICE shows it to be more on the order of 4.46 kΩ. The simulation results are the same as before, but with this approach the only freedom of choice given the design requirements is the value of $R_F$.

To see an example Excel worksheet, go to http://www.ti.com/lit/zip/slyt341 and click Open to view the WinZip directory online (or click Save to download the WinZip file for offline use). Then open the spreadsheet file FDA_Attenuator_Examples_SE_Bipolar_Input.xls and select the Bipolar SE FDA RF_RG Atten worksheet tab. To see a TINA-TI simulation of the circuit in Example 4, follow the same procedure as for Example 3a, but view the bottom circuit labeled "Example 4." Note that the circuit provides the same results as those shown in Figure 3 of Part 1.

## Conclusion

We have analyzed two approaches that attenuate and level-shift high-amplitude, SE bipolar signals to the input range of lower-voltage input ADCs. The first approach (Example 3a) uses an input attenuator with values chosen to provide the required attenuation and to keep the noise gain of the FDA equal to 2 for stability. We saw in the simulation of this example that there is a potential problem with input common-mode voltage that we can solve by using pull-up resistors from the inputs (Example 3b). The second approach (Example 4) uses the gain-setting resistors of the FDA in much the same way as using an inverting op amp, then a resistor is bootstrapped across the inputs to provide a noise gain of 2. Except for the potential problem with the input common-mode voltage in Example 3a, the approaches in Examples 3a and 4 yield the same voltage translation that is needed to accomplish the interface task. Other performance metrics were not analyzed here, but the two approaches have substantially the same noise, bandwidth, and other AC and DC performance characteristics as long as the value of $R_F$ is the same.

The input-attenuator approach in Example 3a is more complex but allows the input impedance to be adjusted independently from the gain-setting resistors used around the FDA. At least to a certain degree, lower values can easily be achieved if desired, but there is a maximum allowable $R_S$ where larger values require the $R_{G+}$ resistor to be a negative value. For example, setting $R_S = 4\ k\Omega$ results in $R_{G+} = 0\ \Omega$. The spreadsheet tool provided will generate "#NUM!" errors for this input as it tries to calculate the nearest standard value, which then replicates throughout the rest of the cells that require a value for $R_{G+}$; but this value will work.

The approach in Example 4 is easier, but the input impedance is set as a multiplication of the feedback resistor and attenuation: $Z_{IN} \approx 2 \times R_F \times$ Attenuation. This does allow some design flexibility by varying the value of $R_F$, but the impact on noise, bandwidth, distortion, and other performance characteristics should be considered.

One final note: The source impedance will affect the input gain or attenuation of either circuit and should be included in the value of $R_S$, especially if it is significant.

## References

For more information related to this article, you can download an Acrobat® Reader® file at www-s.ti.com/sc/techlit/*litnumber* and replace "*litnumber*" with the **TI Lit. #** for the materials listed below.

| **Document Title** | **TI Lit. #** |
|---|---|
| 1. Jim Karki, "Fully-Differential Amplifiers," Application Report | sloa054 |
| 2. Jim Karki, "Using Fully Differential Op Amps as Attenuators, Part 1: Differential Bipolar Input Signals," *Analog Applications Journal* (2Q 2009) | slyt336 |

## Related Web sites

**amplifier.ti.com**

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Replace *partnumber* with ADS8321, THS4509, or THS4520

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